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SCIENTIFIC AMERICAN

FEBRUARY 1998

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WRAPPING UP
THE UNIVERSE

11-Dimensional Bubbles
May Hold Answers
to Why Matter Exists

Both a bird and a dinosaur



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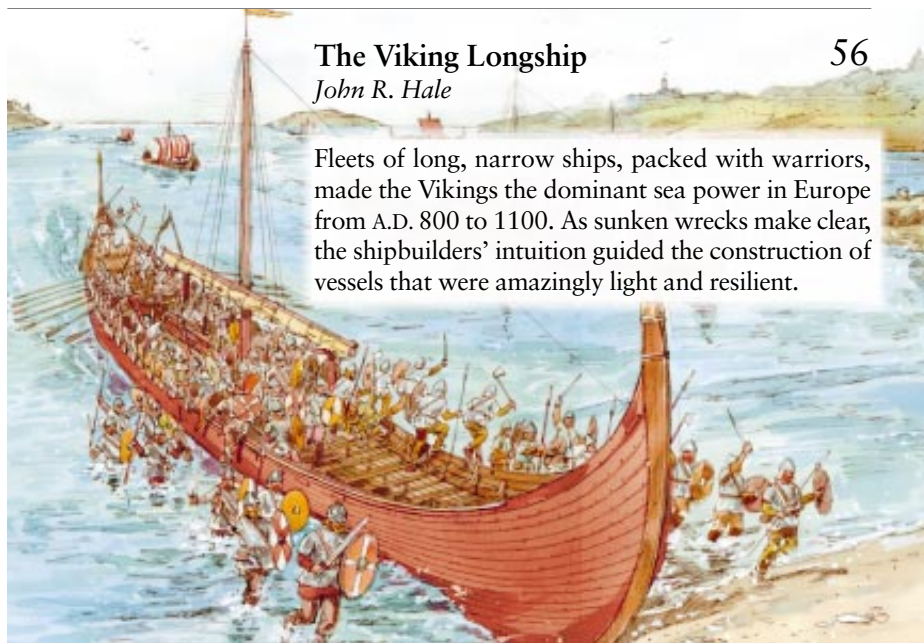


The Origin of Birds and Their Flight

Kevin Padian and Luis M. Chiappe

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Fossil discoveries and anatomical evidence now overwhelmingly confirm that birds descended from small, two-legged, meat-eating dinosaurs. Birds can in fact be classified as dinosaurs—specifically, as members of the theropod lineage. Feathers and other “definitively” avian features seem to have appeared first as hunting adaptations in speedy, ground-based animals. Only later were they co-opted and refined for flight by the group recognized as birds.



The Viking Longship

John R. Hale

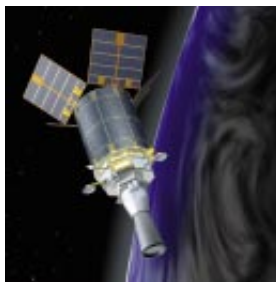
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Fleets of long, narrow ships, packed with warriors, made the Vikings the dominant sea power in Europe from A.D. 800 to 1100. As sunken wrecks make clear, the shipbuilders' intuition guided the construction of vessels that were amazingly light and resilient.

48 Scientists in Black

Jeffrey T. Richelson

Call it “the data that came in from the cold.” Since 1992 U.S. intelligence has shared archives of spy satellite images and other secret records with environmental scientists. This collaboration has been fruitful but poses thorny questions about basing research on classified information.



64 The Theory Formerly Known as Strings

Michael J. Duff

String theory unraveled, but before it did, physicists thought they might explain how the particles and forces of our world arose. New hopes are pinned on “membranes,” bubbles tangled through 11 dimensions of space-time. Membranes can disguise themselves as strings yet provide more answers.



72 The Search for Blood Substitutes

Mary L. Nucci and Abraham Abuchowski

Whole blood, essential for modern medicine, is also difficult to store, increasingly hard to obtain and viewed with suspicion by the public. Work on artificial substitutes is under way, some of them based on hemoglobin (the blood’s oxygen-carrying pigment) and some on totally synthetic chemicals.



80 Greenland Ice Cores: Frozen in Time

Richard B. Alley and Michael L. Bender

For tens of thousands of years, ice accumulating in Greenland has preserved details of the earth’s climate and atmosphere. By extracting samples that run kilometers deep, researchers can peer directly into the past. Hidden in that ancient ice are subtle clues as to when the next ice age might begin.



86 Everyday Exposure to Toxic Pollutants

Wayne R. Ott and John W. Roberts

Your greatest exposure to toxic chemicals may not come from that factory or dump site in the neighborhood—it may come from your living-room carpet. Most of the pollutants reaching people’s bodies today come from materials intentionally or unintentionally brought into the home.



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and botanical gardens.

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About the Cover

Confuciusornis, a primitive bird from the Late Jurassic or Early Cretaceous, retained the sharply clawed fingers of its dinosaurian ancestors. It grew to about the size of a crow. Painting by Sano Kazuhiko.

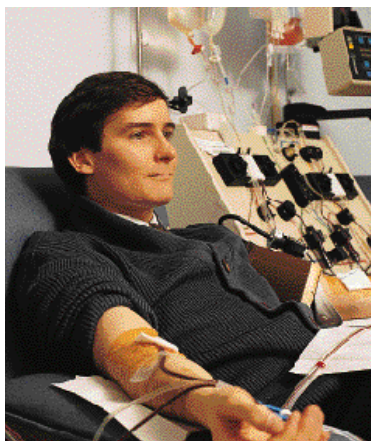
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Saving at the Blood Bank

Valentine's Day abounds with hearts, but this month let me redirect your attention to the blood. Every few weeks I like to lend out all of mine. But it's for a very short term loan—under two hours overall—and no more than a small amount is missing from my body at any moment. Care to join me?

Over the past nine years or so, I've regularly participated in a platelet apheresis program through the New York Blood Center. Apheresis is a donation procedure in which medical technicians harvest just one part of the complex mixture that makes up whole blood. For many hospitalized patients, a transfusion of whole blood would be like a nine-course banquet for breakfast—too much of a good thing. People under treatment for cancer or burns, for example, may have plenty of the red cells that carry oxygen. But they can desperately lack platelets, the cells that help blood to clot. Without a platelet transfusion, such patients could die from minor internal hemorrhages.

Out of necessity, blood banks formerly scavenged six or more donated units of precious whole blood for a single unit of platelets. Then came apheresis, a while-you-wait system for taking cells selectively.



'ROUND AND 'ROUND IT GOES:
spinning blood for precious cells.

Here's a donor's-eye view of the process. While I recline on a lounge, a tube withdraws blood continuously from my left arm and passes it to a sterile centrifuge called a cell separator. It spins the incoming blood to separate the components by density. The cloudy, straw-colored fraction holding platelets siphons into a collection bag. The rest, along with some saline, returns by another tube to my right arm. ("One arm" machines get by with a single tube by cyclically drawing and returning a little blood at a time.) Ninety minutes provides a unit's worth of platelets—too little to harm me but enough to save a life. Later, I don't even feel woozy, and at the snack table I get juice and cookies, which puts me way ahead for the day.

Beginning on page 72, Mary L. Nucci and Abraham Abuchowski discuss "The Search for Blood Substitutes," a quest driven by the certainty that rising need will outstrip supply. Today most of that search concentrates on finding replacements for vital red blood cells. Success in that endeavor won't end the need for blood donations, however. Contact the Red Cross, hospitals or other blood services in your area to find out how you might donate platelets, white blood cells, plasma or the whole crimson package. Trust me, nothing else does more good with less effort.

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LETTERS TO THE EDITORS

FUTURE OF TRANSPORTATION

Compliments on a stimulating special issue on the future of transportation. I disagree, however, with Gary Stix's negative assessment of magnetic levitation ["Maglev: Racing to Oblivion?" October 1997]. The article overlooks the time savings of maglev over a high-speed railroad

in a 500-kilometer (300-mile) radius. Because of faster acceleration, higher speeds around curves and the ability to climb steeper grades, a maglev train can make every stop and still equal the travel time of a nonstop railroad. Had *Scientific American* been published in 1807, when Robert Fulton was developing the first steamship service between New York City and Albany, perhaps we would have read an article entitled "Steamships: Racing to Oblivion." The article would probably have pointed out that the latest Hudson River sloops, with a mild wind, can make the journey in about the same time and at a much lower cost. Why would we want to invest in what many engineers were calling "Fulton's Folly?" There was no way of anticipating the speedy and efficient ships that would eventually evolve from the technology deployed in 1807; similarly, the limits of maglev are yet to be seen.

DANIEL PATRICK MOYNIHAN
U.S. Senator, New York

TOP OF THEIR GAME

The article "The Discovery of the Top Quark," by Tony M. Liss and Paul L. Tipton [September 1997] gave a good firsthand account of the recent observation of the top quark and successfully captured the way discoveries are made within large scientific teams. As members of the rival experiment, DØ, and as young scientists who wrote their Ph.D. theses on the search for the top

quark, we too experienced a combination of jubilation and frustration during this incredible time. All the people involved will certainly remember this period as one of the most exciting of their lives (perhaps because we got so little sleep?). There is one point we would like to correct with respect to the analysis of the DØ experiment. Contrary to what was reported in the article, at the time that Collider Detector at Fermilab (CDF) first claimed an excess of events attributable to the top quark (April 22, 1994), our studies were indeed optimized for a very heavy top. And the top production rate that DØ reported in April 1994, though not sufficient to claim discovery, is closer to the present world average than the corresponding rate reported by CDF at the time.

JIM COCHRAN
University of California, Riverside
JOEY THOMPSON
University of Maryland

WHAT'S IN A NAME?

Wendy M. Grossman's conclusion, in the article "Master of Your Domain" [News and Analysis, "Cyber View," October 1997], that more research is needed on how to structure domain names on the Internet shows a scientific attitude that we do not have time for with the Net. The statement that the proposed plan will not handle changes and broken rules is strange considering that it is a more decentralized and more flexible scheme than the present system, which has survived more than 10 years of exponential growth.

The fact that the new scheme promoted by the Internet Society and others has been controversial is no surprise. But after a year of discussion, we are reaching a rough consensus that serves as the basis for the development of Internet standards by the Internet Engineering Task Force. This plan is supported by industry and consumers. It is not directly supported by governments, but that should not be a drawback: the Internet has so far developed with industry self-regulation and should continue to do so.

FRODE GREISEN
Chairman of the Internet Society
Denmark

VIROSES AND MENTAL ILLNESS

Tim Beardsley's article "Matter over Mind" [News and Analysis, October 1997] raises the issue of whether viruses could cause mental illness. I don't see why the proposal should be controversial. The medical community is already aware of several kinds of infection that can cause mental illness. For instance, infections by the spirochete bacteria that cause syphilis or Lyme disease have been shown, in some (untreated) patients, to lead to hallucinations, paranoia and dementia. Both these infections tend to take a long time to develop. Syphilis may infect someone for 20 years before the first mental symptoms appear, and when the symptoms do appear, they may not at first be recognized as caused by the disease.

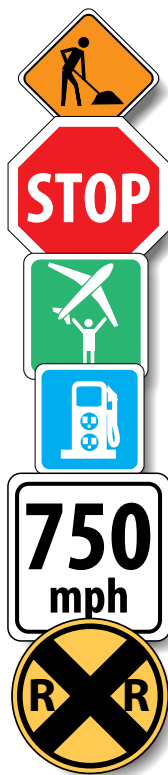
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ERRATA

"Death in the Deep" [News and Analysis, November 1997] implied that 56 percent of excess nitrogen in the Mississippi River is from fertilizer runoff. The data discussed actually refer to estimated inputs of nitrogen to the Mississippi watershed. Fertilizer may provide a smaller proportion of nitrogen reaching the river. With regard to oil recovery before the 1980s, "Oil in 4-D" [News and Analysis, November 1997] should have stated that one barrel out of every three could be recovered.

In "Mercury: The Forgotten Planet" [November 1997], it was stated that the planet has "a dawn-to-dusk day of 176 Earth-days." The statement should have read "a dawn-to-dawn day of 176 Earth-days."



50, 100 AND 150 YEARS AGO



FEBRUARY 1948

POLYSTYRENE—"During the war this country built plants to produce huge quantities of styrene, a key ingredient of a variety of synthetic rubber. It happens that styrene may also be polymerized into polystyrene, a cheap and versatile thermoplastic. Polystyrene is already on its way to becoming the heavy industry of the plastics field. From a starting figure of 100,000 pounds in 1937, installed capacity at the end of this year will top 150,000,000 pounds. One industry alone, the manufacture of home refrigerators, is expected to consume 8,000,000 pounds of polystyrene this year."

FEBRUARY 1898

BATTLESHIP "MAINE" SUNK—"In view of the strained relations existing between the Spanish government and our own, the American people were fully justified in their first exclamation of 'Treachery!' when they learned that their warship had been blown up at the dead of night in the Spanish harbor of Havana. However, the public soon realized that it would be fatal to make charges of crime in the absence of any proof that a crime had been committed. The vessel may have been struck by a torpedo, but accidental causes may have been fire due to spontaneous combustion of coal in the bunkers or decomposition of the high explosives on board, or from a short-circuited electric wire."

QUININE IN INDIA—"There was a time when the government of India had to import annually \$250,000 worth of quinine, and did not get enough of it even then. After a great many experiments, the cultivation of the cinchona tree was made successful in India, and now there are 4,000,000 trees in Bengal, and every rural post office in India sells a five-grain packet of the drug for half a cent, while the government makes from \$2,000 to \$3,500 a year out of the profits."

SPIDER AND FLY—"Our illustration shows one of the most interesting of a series of illusions which depend upon mirrors. The scenario given by the conjurer is that a house was deserted for such a long time that the steps were covered by a gigantic spider's web, which the spectator is surprised to see attended by

a huge spider bearing a lady's head. The secret of the trick is that a mirror lies at an angle of 45° affixed to one of the steps, and reflects the lower steps. A semicircular notch on the top edge of the mirror receives the lady's head, and her body is concealed behind the glass. The spider's body itself is fastened to the network of rope."

FEBRUARY 1848

COAL AT THE POLE?—"In his lecture on the Sun, Prof. Nichol alluded to the fact that fields of coal have been discovered in the polar regions of our earth. This fact plainly indicates that portion of our planet was once lighted and warmed by an agent more powerful than any which now reaches it, and which was capable of sustaining vegetation of a tropical character."

NO BRAIN—"The brain may be removed, be cut away down to the corpus callosum, without destroying life. The animal lives and performs all those functions which are necessary to vitality but has no longer a mind; it cannot think or feel. It requires that food should be pushed into its stomach; once there, it is digested; and the animal will then thrive and grow fat."

WHALING BUSINESS—"The Nantucket Enquirer draws a discouraging picture of the prospects of the whaling business in that place. Since the year 1843 the whaling business has been diminished by fifteen sail, by shipwreck, sales, &c. The voyages are said to be one third longer than they were twenty years ago, and the number of arrivals and departures is constantly growing less and less.

The consumption of whale oil has been decreasing for a long time as well as the supply. Other carbonic materials are now applied to purposes for which fish oil at one time was alone used."

COMPRESSIBILITY—"All known bodies are capable of having their dimensions reduced by pressure or percussion without diminishing their mass. This is a strong proof that all bodies are composed of atoms, the spaces between which may be diminished."

WINTER WIND—"In Franconia, N.H., the weather is said to be so cold that the natives lather their faces and run out of doors, where the wind cuts their beards off."



The spider and the fly illusion

NEWS AND ANALYSIS

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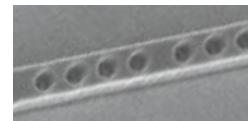


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IN FOCUS

BROOKHAVEN BROUHAHA

The laboratory tries to recover from the public-relations fallout of radioactive leaks and chemical dumping

Since January 1997, when water laced with radioactive tritium was found leaking from an underground tank, Brookhaven National Laboratory in Upton, N.Y., has been battered by its neighbors' fury. Daily newspaper headlines and calls by local legislators for the laboratory's shutdown prompted its director to resign and the Department of Energy, which owns BNL, to dismiss Associated Universities, Inc., a consortium of universities that had operated the lab since its founding in 1947. In December the DOE announced the new contractor team: Brookhaven Science Associates, comprising the State University of New York at Stony Brook and Batelle Memorial Research Institute.

The lab's employees at last breathed a sigh of relief. "A lot of the uncertainty has gone away," says William E. Gunther, director of environmental safety. In addition to the High Flux Beam Reactor, whose spent fuel elements were cooled in the offending pool, BNL contains a medical reactor, an accelerator, an intense light source and other facilities where researchers conduct studies in physics, biology, chemistry and engineering. But New York Senator Alfonse M. D'Amato and Representative Michael P. Forbes have now pushed through legislation requiring that the disputed reactor, which produced neutrons for studying biological and industrial materials, never be restarted.



COURTESY OF BROOKHAVEN NATIONAL LABORATORY

HIGH FLUX BEAM REACTOR

has been shut down since tritium was found to be leaking from a pool in which its spent fuel elements cooled.

"Numbers in general the public doesn't do well with," explains Peter D. Bond, interim director of the lab, of the debacle. Some Brookhaven officials believe their real problem is the nonscientist's hysterical response to the word "radioactive." Mona S. Rowe of the public-affairs office points out that drinking two liters of the most contaminated water every day for a year will subject a person to 50 millirems of radiation, whereas the average Long Islander receives 300 millirems a year from natural sources such as radon. She bitterly bemoans the public's ignorance of science (and that of visiting journalists such as this one) for making the leak seem more ominous than it is.

Although parts of the underground plume have 50 times the drinking-water standard of tritium, it lies well within Brookhaven's limits and will in all probability never endanger anyone. Of far more pressing concern are the chemicals. In 1989 Brookhaven was designated a Superfund site because

of substances dumped into the ground during the 1970s and before (at which time such practices were apparently common and legal). By 1995 the lab had discovered five plumes, containing solvents and a pesticide, leaving its southern boundaries. Although these plumes were too deep to affect residential water wells, the DOE offered public water hookups to residents south of the lab. The announcement led to an uproar and a \$1-billion lawsuit against Brookhaven that is still unresolved.

"Everything the family happens to have is blamed on us," Rowe complains of neighbors who insist they suffer from a variety of ailments resulting from BNL's contamination. Tracing any such effects is a complicated affair. In the mid-1980s county officials found one residential well containing trichloroethane from the lab, which subsequently installed a filter. Although data from about 25 local wells out of 675 recently reviewed by the Agency for Toxic Substances and Disease Registry (ATSDR) showed contaminants at or above the drinking-water standard, Joseph H. Baier of the Suffolk County Department of Health says the substances originate not from BNL but from an abandoned industrial park, household use of drain cleaners and random other sources. Moreover, explains the ATSDR's Andrew Dudley, the drinking-water standards are extremely conservative, so the agency's report concludes that the contamination is "not expected to cause non-cancerous effects."

Because the wells had not been monitored for chemicals before 1985, the agency could say little about the possibility of cancers, which can take several decades to appear. But an epidemiological study led by Roger C. Grimson of S.U.N.Y. at Stony Brook found lower levels for 11 cancers within a 24-kilometer radius of Brookhaven than in control regions outside that circle. (The study unexpectedly revealed an anomalously high rate of breast cancer at the eastern end of Long Island.)

Also of concern to the lab's neighbors is the tritium routinely discharged from its on-site sewage treatment plant into the Peconic River. Although the concentration is well below the drinking-water standard, Bill Smith of Fish Unlimited, a local conservation group, says tritium shows up in local fish and raccoons. Adela Salame-Alfie of the New York State Department of Health asserts that the tritium is not a concern. Although the fish have more radioactivity than usual because of strontium and cesium from Brookhaven, eating 30 grams of it every day for a year would subject a person to less than one millirem of radiation, well within prescribed limits. Most recently, elevated levels of mercury have shown up in river-bottom sediments near the sewage treatment plant as well as in local fish, and the laboratory is planning a remediation scheme. Summarizes Baier: "[Brookhaven officials are] lucky to have a very large site—the things they've discarded have

remained for the most part on site. If it was a small site, it would be all over the landscape."

Unfortunately for the lab, new leaks keep turning up, such as of strontium from a decommissioned reactor. Although both radioactive plumes lie well within the perimeter and are therefore not hazardous, they signal a problem deeper than public relations. Associated Universities ran Brookhaven in an informal manner, maintaining a "university atmosphere" that favored basic research. But a DOE report notes that the informality was "not conducive to providing the level of discipline and control" necessary for ensuring safety. So although Brookhaven scientists recently discovered an exotic meson, a new particle a mere 10^{-13} centimeter in extent, its staff was unable to detect 20 to 35 liters of tritiated water leaking every day for a decade (despite repeated tests of the pool's level).

It was only after local county officials had nagged for several years that the lab drilled test wells near the tritium pool.

"They looked at it as proving the obvious, that there is nothing wrong," Baier recalls. But there was. The DOE is requiring the new contractor to put in place strict procedures for ensuring environmental safety. John H. Marburger, who will take over in March as the lab's director, says science managers will become responsible for safety and environment, not just for research. K. Dean Helms, senior representative of the DOE at Brookhaven, says his office has also made vigorous efforts to address the concerns of the community, which "is pleased at the level of openness we have brought in."

Brookhaven's troubles are far from over. Forbes remains

adamantly opposed to restarting the High Flux Beam Reactor, even though it is not directly implicated in the tritium leak. "Given the age of the reactor [32 years], no one can guarantee that further incidents will not occur," says a spokesperson for Forbes. The DOE is about to begin a year-long study of the safety and environmental impact of the reactor. If all concerns are met, Helms says, Congress will have to decide whether or not to restart it. Rowe is convinced that if the reactor goes for good, the activists currently targeting the lab will just shift their sights to its other (medical) reactor, where clinical trials on brain tumors are being carried out.

The DOE has high stakes at Brookhaven, which will house the Relativistic Heavy Ion Collider, a new facility for particle physics due to start in 1999. But the tritium affair has also caused it another headache. In reviewing the events surrounding the leak, the General Accounting Office sharply criticized the DOE's multiple and muddled chains of command on environmental issues. Helms says the DOE is now "looking across the whole laboratory system to see what lessons learned from Brookhaven can be applied." The fallout from the radioactivity may, in the end, reach far beyond Brookhaven's borders.

—Madhusree Mukerjee



BROOKHAVEN EMPLOYEES
protest Representative Michael P. Forbes's denunciation
of the High Flux Beam Reactor.

COURTESY OF BROOKHAVEN NATIONAL LABORATORY

EXPERIMENTAL ASTROPHYSICS

PLAYING WITH STARS

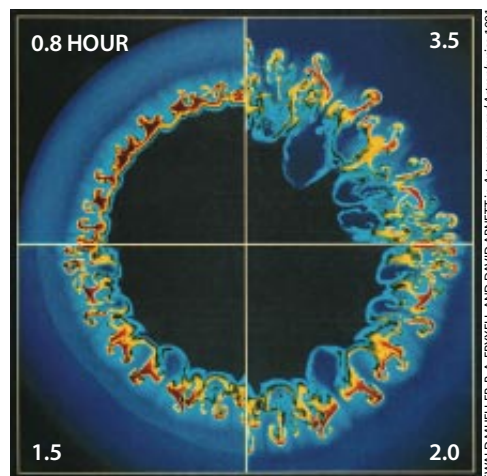
A three-story laser may help solve the mysteries posed by an exploding star

Eleven years ago this February 23, stargazers watching the southern sky marveled as a nondescript speck in a neighboring galaxy burst into a brilliant blob. About 160,000 years earlier the giant blue star had run out of fuel; its iron center had collapsed and rebounded in a colossal shock wave. The resulting flash that at last hit the earth that February day revealed that the core of Supernova 1987A had released in just the first 10 seconds of its implosion as much energy as all the other visible stars and galaxies in the universe combined.

Simulating such a phenomenal blast in a lab experiment might smack of hubris. But physicists at Lawrence Livermore National Laboratory have used the Nova laser, the world's second most powerful (after the Omega laser at the University of Rochester), to create conditions comparable to those that propelled the outer shell of the exploding star.

Obviously they do so at a much smaller scale. Standing atop the five-meter-wide sphere in which Nova's 10 mammoth beams collide, Livermore physicist Bruce Remington gingerly shows me the target onto which 30 trillion watts will soon be focused. For something that costs about \$10,000, it doesn't look like much: a three-millimeter-long gold cylinder with a two-layer patch of plastic and copper grafted into its wall. In the center of that patch, a dimple, smaller than my eyes can make out, has been pressed. This dimple, graduate student Jave Kane assures me, will follow the same laws of hydrodynamics as a chunk of supernova—just 300 billion times faster and 40 trillion times smaller.

The target is lowered into the chamber, and we retire to the safety of the control room, where technicians have centered the cylinder in their crosshairs. At a keystroke, electricity begins flooding 10,000 large capacitors in the basement. The lights, alas, do not dim or even flicker as I had hoped. The only sign of the energy pooling underneath us is a green bar rising on a monitor to reach one megajoule, then two. A voice overhead counts—three, two, one—and with no more fanfare than a modest bang,



SIMULATED SUPERNOVA,
shown evolving over 3.5 hours, does not fully explain the strange behavior of SN 1987A.

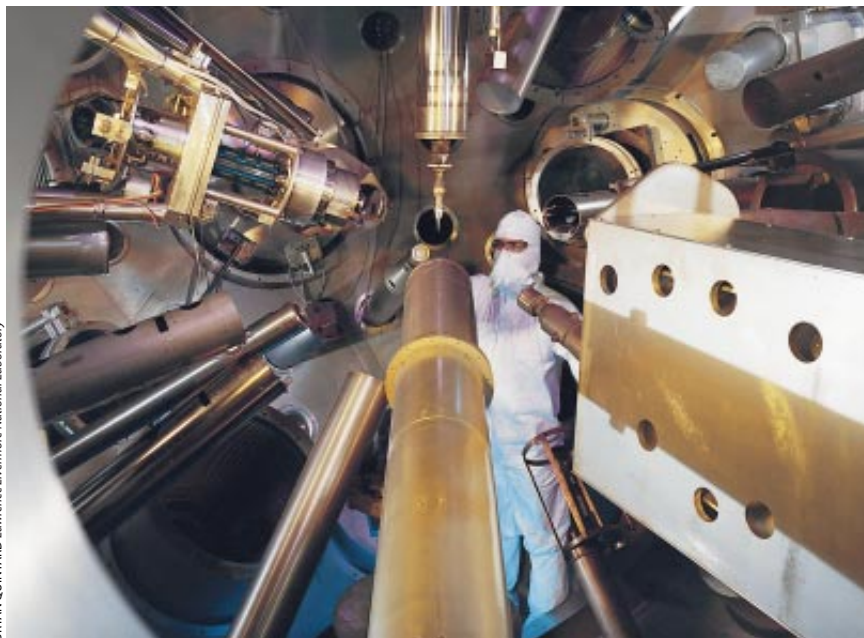
the capacitors release their thunderbolt. The juice surges into 10 lasers, and their nanosecond pulses of light run 10 gauntlets of flash lamps, each of which adds to the pulses' energy.

At last the beams converge on the inside of the gold cylinder, vaporizing it in a shower of x-rays. As the x-rays pass through the copper-plastic patch, turning it into a seething plasma, a camera snaps 16 pictures, each timed to within 100 trillionths of a second.

Pictures taken during more than 30 laser shots over the past three years look remarkably like those produced by computer simulations of supernovas. "With minor adaptations, the supernova codes model these experiments quite well—at least when we stick to two dimensions," Kane says. But the simulations failed miserably when they were applied to the three-dimensional behavior of Supernova 1987A: it ejected inner material at twice the speed that astrophysicists had predicted. That third dimension may make all the difference.

Remington and his colleagues hope the numbers they gather by vaporizing 3-D dimples will, scaled to cosmic proportions, help them explain the messy explosion of Supernova 1987A. If they hurry, they may even finish their predictions in time to test them at the next great spectacle in the life of this star. In the next five years, stellar shrapnel is expected to crash into an hourglass-shaped halo that the star cast off in an earlier stage of its life.

—W. Wayt Gibbs in Livermore, Calif.



30-TRILLION-WATT NOVA LASER
causes a tiny target at the center to bubble like a supernova shell.

POLITICS AND PCB

*Speaking out may have cost
a researcher his position*

Is he an outspoken canary in a coal mine for humans suffering from slow poison or a careless scientist warning of imaginary dangers? Brian Bush has spent more than 25 years studying polychlorinated biphenyls (PCBs) at the Wadsworth Center of the New York State Department of Health in Albany and is an internationally recognized authority on the chemicals' effects on human tissue. Last fall his superiors summarily transferred him, effectively closing down his research. The state cited incompetence, but Bush's supporters argue that the move was intended to silence Bush, who during the past year had begun speaking publicly about apparently unrecognized dangers of inhaling PCBs.

Bush was the principal investigator of PCB research informally called the Akwesasne study (it includes tissue samples from a Mohawk tribe living near a PCB dump site created by General Motors near Massena, N.Y.). The research is shared by universities from Syracuse to Albany and ranges from ways to detoxify PCBs to determining their effects on children exposed in utero.

PCBs are stable, artificial substances first made around 1890 and can occur as by-products of combustion. Since 1929 they have spread globally, appearing in electrical products, paints, automobiles and other consumer goods and as waste products in landfills and rivers. Of 209 PCB congeners, or variants, theoretically possible, about 120 were manufactured. In total, at least 450 million kilograms (one billion pounds) of the compound are essentially loose in the environment, according to a 1992 study conducted by the World Wildlife Fund.

PCBs are notorious for accumulating in the food chain, as they have a special affinity for fat tissue. Eggs and fledglings of some tree swallows near PCB sites in the upper Hudson River basin, for instance, are literally hazardous waste: Anne Secord of the U.S. Fish and Wildlife Service and her colleagues found in 1994 that their PCB concentrations exceeded the federal threshold of 50 parts per million. The birds show a range of

ANTI GRAVITY

Whatchamacallit

If you went by the moniker "Dr. Math," you too might take an inordinate interest in names. So it was that Kevin Math, head of musculoskeletal radiology at Beth Israel Medical Center in New York City, found himself contemplating the high occurrence of medical conditions that even physicians often describe with simple, everyday names. For instance, why struggle through the jawbreaking "lateral epicondylitis" when "tennis elbow" tells the story? Math assembled a collection of such conditions and delivered a presentation on the subject at the annual meeting of the Radiological Society of North America in Chicago last December.

Although every discipline has its own jargon, the preference for simple language in some cases improves communication between doctor and patient. For example, if you spent a lot of time on all fours and got prepatellar bursitis, you might think you had a rare, devastating condition. "But," Math notes, "if I say, 'Oh, you have housemaid's knee,' they can relate to it more."

Some of the maladies that befall the musculoskeletal system give rise to colorful common names that hark back to simpler, yet hazardous, technological times. A break to the radial styloid, a wristbone, still goes by the name chauffeur's fracture, as it was an injury suffered in the days when one, or preferably one's chauffeur, had to turn a hand crank to rev up the Studebaker. On unrare occasions, the engine would backfire, the crank would whip around backward, and, in a snap, one hand could no longer wash the other. Today the injury is associated with car accidents or falling on icy walks, but the name remains.

Injury to the ulnar collateral ligament of the metacarpophalangeal joint trips off the tongue more agreeably as gamekeeper's thumb. The name comes from the chronic ligament damage incurred by Scottish gamekeepers in the course of killing wounded rabbits. "The gamekeepers would grasp the hare's neck between the base of the thumb and index finger," Math explains, "and repetitively twist and hyperextend the

neck." If that tale of hare curling doesn't curl your hair, consider this: "The activity would have to be repeated thousands of times before the ligament would get stressed to that degree," Math notes. "The less busy gamekeepers were probably not bothered by this condition." The same thumb damage can result during a fall while skiing, from the torque of the pole strap. Math says, however, that doctors still refer to gamekeeper's thumb more than skier's thumb, even though schussers presumably outnumber hare pullers.

Don Juan's fracture conjures up interesting images, but this malady is actually a break at the heel, which, of course, was what quite a few bursitic housemaids considered Don Juan to be. The injury, also called lover's frac-



ture, refers to damage usually caused by a fall, the kind "that might result from someone trying to escape out a window when a jealous husband comes home," Math speculates. More common causes include ladder accidents or hard skydiving landings.

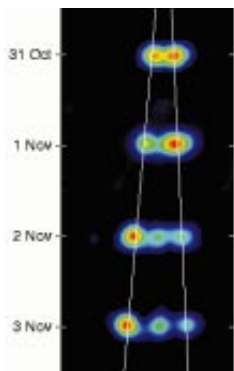
Math created an eponym of his own, an alternative to housemaid's knee, when one of his patients took umbrage at that designation. "He was a longshoreman from Brooklyn," Math recalls. "I told him, 'You have a very typical finding on your x-ray, this swelling in front of your kneecap. It's referred to as housemaid's knee.'" A period of silence followed, according to Math, after which the longshoreman said, "Whadya talkin' about? I was just layin' down tile all weekend." In the interests of harmony and the avoidance of bad boxer's face, Math responded quickly with, "Well, it's also called tilelayer's knee." This diagnosis satisfied the burly patient, who limped away content with his masculine ache. —Steve Mirsky

IN BRIEF

Black Hole Blasts

Only MERLIN—the Multi Element Radio Linked Interferometer Network—could have captured the event: In late October

MERLIN



the instrument, which is run by the University of Manchester, recorded a series of explosions coming from GRS1915, a black hole some 40,000 light-years away on the other side of the Milky Way. Matter spiraling into GRS1915, which is several times more massive than our sun, violently shot out two

streams of ultrahot gas. These jets moved in opposite directions at velocities greater than 90 percent of the speed of light.

Biotic Bargain

David Pimentel and eight graduate students at Cornell University's College of Agriculture and Life Sciences recently figured the tab for services we get free from the planet's plants, animals and microorganisms. The total came to \$319 billion for the U.S. and \$2.9 trillion for the world. Some of the charges:

	BILLIONS OF DOLLARS	
	U.S.	World
WASTE DISPOSAL	62	760
NITROGEN FIXATION	8	90
POLLINATION	40	200
ECOTOURISM	18	500
CO ₂ SEQUESTRATION	6	135

Extending Life

New clues about the genetics of aging are emerging. First, Cynthia Kenyon of the University of California at San Francisco reported in *Science* that the activity of a single gene can double the life span of the nematode *C. elegans*. The gene, *daf-16*, is related to so-called forkhead genes, which encode tined proteins that can attach to and control stretches of DNA. Second, Marc Tatar of Brown University, working with colleagues from the University of Minnesota, published results in *Nature* showing that flies bred to contain extra copies of heat-shock protein 70 produce a lot of it when they are exposed to warmth, and this abundance substantially increases their life span.

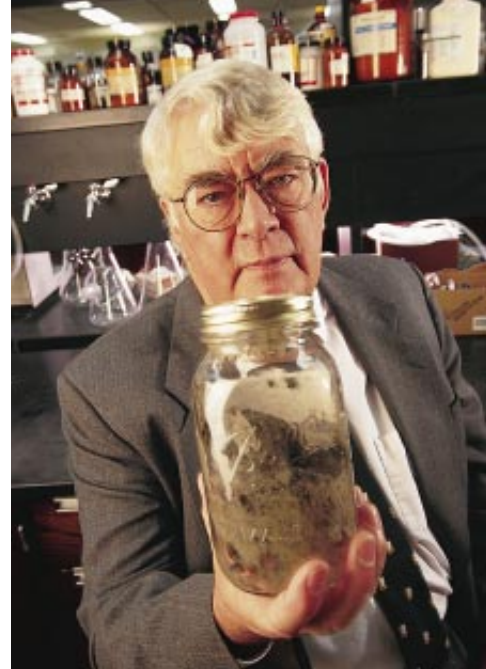
effects, from crossed bills and odd plumage patterns to an inability to construct proper nests.

The federal government lists PCBs as probable carcinogens, but that may not be their main harm. "Many of the symptoms in humans exposed to PCBs are related to the nervous system and behavior," writes David O. Carpenter, coordinator of the Akwesasne research team and a dean at the State University of New York at Albany. Some congeners kill brain cells in lab tests; they especially seem to affect dopamine, a key brain chemical.

Bush's lab had begun accumulating evidence that suggests PCBs could be more harmful than previously realized. For instance, it found how easily some forms of PCBs become airborne. Since at least 1937, PCBs have been known to volatilize, but no one had tested whether breathing in PCBs harms humans. Moreover, no one knows how far airborne PCBs can travel. Researchers in Canada found that the breast milk of Inuit women in northern Quebec was heavily contaminated with PCBs. Exposure was traced to precipitation that released PCB fallout: the compounds returned up the food chain through fish and seals, which serve as the Inuits' primary food. Bush speculates that the PCBs may have come from New York's Hudson River. Because the river is an estuary, each turn of the tide exposes mudflats, from which PCBs may rapidly volatilize and move off in the air currents.

Bush's pronouncements of the dangers from the airborne spread of PCBs fly in the face of inaction by state health officials and claims made by the corporations that dumped PCBs, such as General Electric. The firms have consistently maintained that the chemicals lie inert at river bottoms and at dump sites and thus are basically harmless in the environment. If further research supports Bush's contentions, then GE and other companies may become liable for billions of dollars in cleanup costs.

That research, though, may not happen soon. Last September Bush received a memo from his superior, stating that he was being transferred to a new assignment, one unconnected with PCBs. According to some of Bush's colleagues, the move forces the cancellation of some grants, which require a level of investigator expertise (without Bush, the team



JAMES LEYNSE SABA

AIRBORNE PCBs FROM SOIL
could pose a hazard, Brian Bush argues.

lacks the necessary aptitude). That has also created a ripple effect: Sheldon Feldman of the Benedictine Hospital in Kingston, N.Y., who studies the relation between PCBs and breast cancer, said he had no place to send samples.

The memo did not explain the move, but health department spokespersons later hinted that Bush's lab work was deficient. The department appointed a five-member committee to investigate, and in December it released what it called a consensus report. The four-page account was critical of some procedures in Bush's lab, noting in summary that "proficiency has been hampered by a lack of proper quality control/quality assurance procedures and a lack of proper data review procedures."

Bush says the report effectively exonerates his work, claiming that his overall conclusions are not challenged. Committee members never actually visited his lab, he said, but spent a day going over paperwork. They found three errors in more than 6,500 data points culled from 63 blood and serum samples. "They are trying to get me because I am a whistle-blower," Bush insists. "But I consider the whole thing as a triumph, because the whole line that PCBs are innocuous has been blown sky-high."

After the release of the report, S.U.N.Y. at Albany offered to set up a laboratory for Bush, enabling him to conduct PCB research on the Albany campus. Bush hopes to resume his studies soon, but nothing is set. Meanwhile we remain uncertain how much harm we inhale.

—Jim Gordon in *Saugerties*, N.Y.

THE PAINTED BIRD

Lawn flamingos come to the aid of ecology

Sunrise is two hours away, and it's as dark as it should be with the moon obscured by clouds. Lisa Borgia tromps knee-deep through a half-acre pond about 20 miles west of West Palm Beach, the beam from a headlight perched atop her mosquito hood slicing the gloom. She admits that she prefers *Star Trek's* ridge-headed Klingon Mr. Worf to Brad Pitt, which may help explain why Borgia, on an internship with the South Florida Water Management District (SFWMD), remains unperturbed by the alligator whose head breaks the surface six feet away. Granted, the reptile is only about two feet long; the big gators eschew the pond, and a more likely source of trouble is the venomous snakes. Even taking Worf into account, the obvious question—What's a nice girl like you doing in a place like this?—takes a backseat to a more immediate query: Why is she carrying those plastic lawn flamingos?

Borgia, fellow flamingo-bearer David K. Kieckbusch and their boss, avian ecologist Dale E. Gawlik, a senior environmental scientist with the SFWMD, have finally found a constructive use for the pink lawn ornaments. A coat of flat white paint transforms the suburban blight into tools for studying how birds use visual cues from their feathered friends to choose feeding sites.

The SFWMD's 15 ponds are perfectly situated for controlled field research on wild subjects—egrets, herons, ibis and wood storks naturally fly in from the adjacent Loxahatchee National Wildlife Refuge. "We focused on things like water depth and prey density," Gawlik says of earlier, flamingo-free experiments aimed at teasing out the relation between wading birds and water supply. The researchers altered environmental factors in the ponds easily—gravity flow from a higher reservoir or into a lower one changes the water level of any pond in minutes. But some of the social cues that determine feeding choices among wading birds remained unknown.

Perhaps decoys could reveal how birds rely on their feathered friends for dining recommendations, the researchers thought. When Borgia found out that hunters' heron decoys run a prohibitive \$30 each, she consulted with Kieckbusch, who had pink flamingos at home, and discovered that the plastic lawn ornaments could be had for \$5.40 a pair. Painted, they make passable egrets.

Previous trials using the fake flamingos showed that birds bypass empty ponds in favor of those with decoys. This mid-November day's experiment will fine-tune the data. Borgia and Kieckbusch set the lawn decorations in either scattered or clustered arrays in ponds of various depths. "The spacing of the flock is an additional cue related to social behavior," Gawlik says.

As we move through the water—a fast, bowlegged waddle helps to minimize sinking into the soft bottom—the mosquitoes attack mercilessly. As well as a nuisance, they're probably more

Come and Get It

In December the Food and Drug Administration at last approved the use of radiation for eliminating harmful microorganisms such as *E. coli* from red meat. For years, companies have irradiated chicken, fruits and vegetables, but there has been little consumer demand for them. They are most often purchased for astronauts and hospital patients—for whom food poisoning could be especially deadly. But several recent outbreaks have made irradiated meats more popular. Treated meat packages, which will bear the label shown here, most likely will appear in markets next summer and should cost only a few cents more than nonirradiated meats.



Snowball Fight

Physicists at the fall meeting of the American Geophysical Union had it out again over the theory that small ice comets continually pelt our planet's upper atmosphere. Louis A. Frank and John B. Sigwarth of the University of Iowa presented new evidence in support of the idea, which they first proposed 11 years ago. They showed that dark spots on photographs taken by NASA's Polar spacecraft change in size depending on their distance from the cameras—which is just what you would expect if the spots marked real comets. But James Spann of the NASA Marshall Space Flight Center argues that the dark spots are simply noise from the cameras and that they also appear when the instruments are on the ground. Only time and more data will tell.

Asbestos Eater

Sounds too good to be true: Scientists at Brookhaven National Laboratory, working with W. R. Grace & Company, have developed a chemical solution that can destroy asbestos in installed fireproofing without ruining the material's ability to resist fire. When this foam was sprayed onto fireproofing made by Grace, it dissolved asbestos fibers into harmless minerals. Because it eliminates the need to remove the older material, the process should reduce costs for building owners. Patents are pending, and the product, which should work on all kinds of fireproofing, is expected to be commercially available by early 1998.

More "In Brief" on next page



PLASTIC FLAMINGOS (foreground) bring in ibis.

STEVE MIRSKY

In Brief, continued from preceding page

After Kyoto

It took 11 marathon days of negotiation, but at last on December 11, delegates at the Third Conference of the Parties to the United Nations Framework Convention on Climate Change in



KATSUMI KASAHARA AP Photo

Kyoto reached an agreement to curb greenhouse gas emissions in the near future. Many charge that the treaty did not go far enough and

that emissions levels will not fall off fast enough to prevent catastrophic global warming. Yet it is unclear whether all of the more than 150 participating countries will ratify the treaty. The U.S., which came away from the table having won less commitment from developing nations than it had wanted, has promised to cut emissions back to 7 percent below 1990 levels. The European Union pledged 8 percent cuts, and Japan signed on for a 6 percent reduction.

Particle Accelerator

For the first time, materials and parts made in the U.S. will be used in a particle accelerator outside the country. Indeed, more than 550 U.S. scientists are collaborating on two massive detectors for the Large Hadron Collider—a particle accelerator, measuring 27 kilometers in circumference, now under construction at CERN, the European laboratory for particle physics near Geneva. The Large Hadron Collider will crash protons into one another at higher energies than ever before.

Checkout Tech

You're next in line, but the guy in front of you is buying some odd piece of fruit, for which the cashier can't seem to find the right scale code. A new gadget could save you from supermarket hell: Alan Gelperin of Princeton, N.J., has been awarded a U.S. patent, which he assigned to NCR Corporation in Dayton, Ohio, for a device that senses the aromas of familiar produce. An induced air-flow wafts past a fruit or vegetable and enters an aperture in the device, activating sensors that prepare a pattern according to the smell. The device then compares the pattern with references and rings you up. —Kristin Leutwyler

dangerous than the gators and snakes: the area is under an encephalitis watch. "If you face into the wind," Borgia advises this slap-happy reporter, "the mosquitoes will gather on your lee. You can keep them off your face." Flamingos set, Borgia and Kieckbusch climb to the decks of separate observation towers, each with a view of half the ponds.

Shortly after first light, real birds join the plastic ones. Like an overwhelmed air-traffic controller, Borgia frantically records the arrivals and departures: "Glossy ibis and tricolor heron leaving [pond number] 8.... Two little blue herons on 9.... Large group of snowies coming in to 8, estimate 60.... Great blue on 11.... Two glossy ibis on 11.... One great and one snowy leaving 11."

The attempt to note the decisions of hundreds of birds continues for almost an hour, by which point the sheer number of real birds drowns out the decoy effect. Borgia and Kieckbusch abandon their roosts and head back into the muck to wrangle the flamingos. They will randomize the water levels and ar-



STEVE MIRSKY

AFTER THE MORNING COUNT Lisa Borgia rounds up the decoys.

rays and repeat the experiment all week. Then they and Gawlik will analyze the data, hoping to fill in another small piece of the large puzzle that is the Everglades ecosystem. Water management decisions critical for the region's wildlife and people depend on such detailed information. The lowly lawn flamingo finally has reason to preen. —Steve Mirsky

ACOUSTICS

BOOM BOX

A resonator boosts sound pressures to new highs

Blowing across the lip of a bottle to produce that satisfying hum would not seem to be the basis for new discoveries. But that is essentially what Timothy S. Lucas claims he has made. Reporting at the Acoustical Society of America meeting last December, the founder and president of Macrosonix Corporation in Richmond, Va., says his torpedo-shaped "bottles," when

shaken back and forth hundreds of times a second, can create standing sound waves within them that pack energy densities 1,600 times greater than that previously achieved in acoustics. The process, which Lucas calls "resonant macrosonic synthesis," can produce pressures exceeding 3.5 million pascals (500 pounds per square inch), more than enough for industrial applications such as compressing and pumping.

The key is the shape of the bottle, or resonator. In the past, resonators were often cylindrical, and shock waves formed inside them if they vibrated too quickly. A shock wave—a compression wave that delineates a sharp boundary between high and low pressures—dissipated energy, preventing the internal pressure from getting too high. As a result, driving the resonator faster—the equivalent of blowing harder across the top of a bottle—would no longer boost the volume of the internal sound.



MACROSONIX CORPORATION

ACOUSTIC "BOTTLE"
driven by a motor breaks a sound barrier.

While at Los Alamos National Laboratory in 1990, Lucas studied how shock waves could be broken down into higher-frequency components, or harmonics. He realized that for resonant waves, the shape of the cavity was the critical factor. Lucas's resonators, which can also be in the shape of bulbs and cones,

cause the harmonics to add up slightly out of step with one another. As a result, there are no overly sudden changes in pressure that lead to shock fronts. Without shock formation, the intensity of sound waves could build up, reaching amplitudes not previously possible.

Currently Lucas and his colleagues are

modeling the acoustics within the cavity: some of the turbulence inside robs energy from the sound wave. Still, the resonator has generated enough sonic power to interest a major appliance manufacturer, which has a license to incorporate the resonator as a compressor in household refrigerators. —Philip Yam

BY THE NUMBERS

Deaths from Excessive Cold and Excessive Heat

In normal years, 600 to 700 Americans die of excessive cold, but unusual winters may raise the annual numbers above 1,000. Aside from a few mountaineers and other athletes, the people who suffer most from extreme cold are generally those living at the edges of society—the homeless, alcohol abusers, people with severe health problems and the elderly poor, particularly those with inadequate nutrition, housing and clothing. Use of certain drugs, such as antipsychotics, increases the risk. Victims are disproportionately male, Native American and black. The higher rate at which blacks die of hypothermia—below-normal body temperature—helps to explain the surprising fact that the death rates shown in the upper map are elevated in much of the South. Normal winter temperatures in the South are generally above freezing, but occasionally they go below. Furthermore, hypothermia may occur at temperatures above freezing, particularly when people are in fairly chilly water for extended periods.

The high death rates from hypothermia in Arizona, New Mexico, the Dakotas, Montana and Alaska reflect primarily the poor living conditions and risky behavior of Native Americans. In Alaska, for example, these individuals are at greater risk than whites because of time spent outdoors far from emergency help. Alcohol is a widespread problem: in New Mexico, for example, where its sale is banned on many reservations, men go long distances to drink. Those who return in cold weather on foot are at high risk of hypothermia.

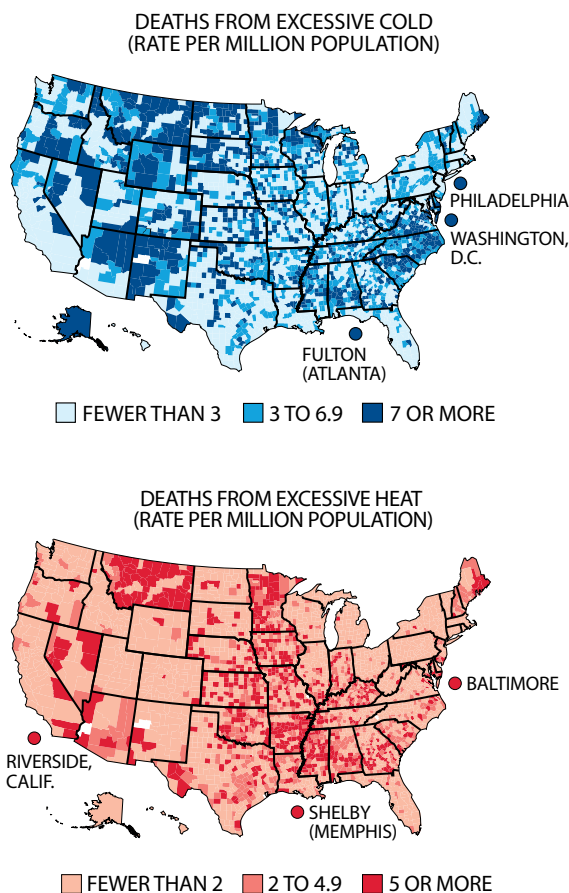
About 240 people die of excessive heat in normal years, but in years that have severe heat waves, the numbers may go as

high as 1,700. In the July heat wave of 1980, daytime temperatures in some cities, such as Memphis, exceeded 38 degrees Celsius (100 degrees Fahrenheit) for more than two weeks on end. In episodes like this, heatstroke often attacks with little warning. Typically, an apparently well person goes to bed and the next day is found seriously ill, unconscious or dead; heatstroke may progress to a life-threatening stage within minutes.

Those who die of hyperthermia—above-normal body temperature—also generally live at the edges of society. They tend to be poor, elderly and black—indeed, blacks account for most of the mortality from hyperthermia in seven Southern and border states. Old people are especially affected in heat waves because of diminished capacity to increase cardiac output and to sweat efficiently. Those who take medications such as major tranquilizers and diuretics have an increased risk of heatstroke. People who live on higher floors of multistory buildings (which tend to be warmer than lower floors), who lack air conditioning and who cannot care for themselves are at particular risk. Many of those who succumb keep doors and windows closed during heat waves for safety reasons.

Extremes of temperature are minor contributors to mortality overall, and furthermore, rates appear to be trending downward. But it is likely that the numbers are underreported for a variety of reasons, such as to save relatives the embarrassment of implied neglect or to shield landlords from the

threat of legal liability. Whatever the true numbers, such deaths are particularly tragic because they are often wholly preventable. —Rodger Doyle (rdoyl2@aol.com)



SOURCE: National Center for Health Statistics. Data are for 1979–1994. The circles indicate those counties among the top 100 most populous with rates in the highest mortality category. Alaska data are for entire state.

PROFILE

Where Science and Religion Meet

The U.S. head of the Human Genome Project, Francis S. Collins, strives to keep his Christianity from interfering with his science and politics

The combination of world-class scientific researcher, savvy political activist, federal program chief and serious Christian is not often found in one person. Yet that constellation of traits is vigorously expressed in Francis S. Collins.

Collins leads the U.S. Human Genome Project, an ambitious effort to analyze the human genetic inheritance in its ultimate molecular detail. A physician by training, he became a scientific superstar in 1989, when he was a researcher at the University of Michigan. There, together with various collaborators, he employed a new technique called positional cloning to find the human gene that, if mutated, can give rise to cystic fibrosis. That discovery quickly made possible the development of tests for prenatal diagnosis of the disease.

Collins has since co-led successful efforts to identify several other genes implicated in serious illness. His tally of discoveries thus far includes genes that play a role in neurofibromatosis and Huntington's disease as well as the rarer ataxia telangiectasia and multiple endocrine neoplasia type 1. In 1993, after turning down the invitation six months earlier, Collins left Michigan to become director of what is now the National Human Genome Research Institute.

In his office on the campus of the National Institutes of Health in Bethesda, Md., the 47-year-old Collins sits at the center of a vortex of medical hopes and fears that is probably unrivaled. He is widely seen as a strong leader for the genome program, which he reports is on target for sequencing the entire three billion bases of human DNA by 2005. And his influence extends well beyond research. Collins's energetic support for laws to prevent people from losing health insurance because of genetic discoveries is perhaps the best explanation for the limitations on gene-based insurance discrimination in the 1996 Kennedy-Kasbaum bill.

Recently Collins has thrown his po-

litical weight behind a new "potentially expensive but very important goal" that he hopes will supplement the genome project's sequencing effort. Collins wants to assemble a public-domain catalogue of subtle human genetic variations known as single nucleotide polymorphisms, written "SNPs" and pronounced "snips." The effort would constitute "a very significant change in the vision of what the genome project might be," Collins says. SNPs are detected by comparing DNA sequences derived from different people.

Unlike positional cloning, analysis of SNPs can readily track down genes that,

though collectively influential, individually play only a small role in causing disease. Diabetes, hypertension and some mental illnesses are among the conditions caused by multiple genes. New DNA "chips," small glass plates incorporating microscopic arrays of nucleic acid sequences, can be used to detect mutations in groups of genes simultaneously. By employing this chip technology, researchers should be able to use SNPs for rapid diagnoses.

Collins now spends a quarter of his time building support at NIH for a SNP repository. He bolsters his case by predicting that, absent a public effort on SNPs, private companies will probably survey these molecular flags and patent them. There may be only 200,000 of the most valuable SNPs, so patents could easily deny researchers the use of them except through "a complicated meshwork of license agreements."

Collins the federal official often retains the open-collar, casual style that is de rigueur among scientists, and his preferred mode of transportation (motorcycle) has earned him some notori-



JAMES SCHNEPP Gamma Liaison Network

GENETIC TESTS HAVE SAVED LIVES,

Francis S. Collins says, but he has "some concerns" that they might be used to abort fetuses with conditions that are less than disastrous.

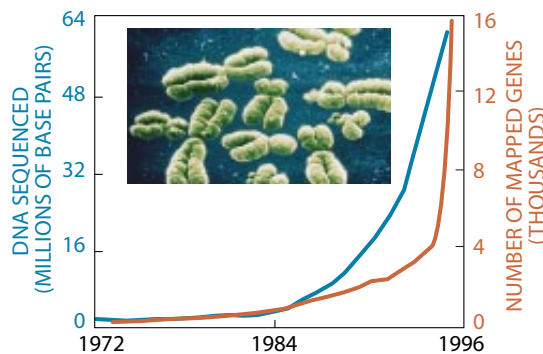
ety. He is, however, more unassuming than officials or scientists are wont to be. He feels "incredibly fortunate" to be standing at the helm of a project "which I think is going to change everything over the years." Such feelings inspire Collins to musical expression. Last year at the annual North American Cystic Fibrosis Conference, he performed his song "Dare to Dream," accompanying himself on guitar. Yet Collins's easygoing demeanor belies intensity not far below the surface: he estimates that 100-hour workweeks are his norm.

He grew up on a farm in Virginia and graduated with a degree in chemistry from the University of Virginia with highest honors. He followed up with a Ph.D. in physical chemistry at Yale University, then went to the University of North Carolina to study medicine. He was soon active in genetics. As a researcher at Michigan, he was doing "exactly what I wanted to do," which is why he turned down the job of leading the genome program the first time he was offered it. He now admits, however, he is "having a very good time."

Large-scale human DNA sequencing was not initiated until 1996, after preliminary mapping had been accomplished. So far only 2 percent of the total human genome has been sequenced. The only cloud on the horizon that Collins foresees is reducing the cost enough to fit the entire project into the budget, \$3 billion over 15 years.

Sequencing now costs 50 cents per base pair. Collins needs to get that figure down to 20 cents. If he could reach 10 cents, the gene sequencers could tackle the mouse as well, something Collins wants to do because comparisons would shed light on how the genome is organized. Cutting against that, however, is the need to ensure reproducibility. This year Collins has enacted cross-laboratory checks to ensure that sequence accuracy stays over 99.99 percent.

Collins notes with satisfaction that today there are people alive who would have died without genetic tests that alerted physicians to problems. Patients with certain types of hereditary colon cancer, which can be treated by surgery, are the most obvious examples. Testing for genes predisposing to multiple endocrine neoplasia type 1 and, possibly, breast and ovarian cancer may in time save lives, Collins judges.



NUMBER OF MAPPED HUMAN GENES,
located on chromosomes (photograph), is rising,
but only some 64 million bases have been completely
sequenced, about 2 percent of a person's total.

Congress funded the genome project hoping it would lead to cures. But for most of the diseases to which Collins has made important contributions, the only intervention at present is abortion of an affected fetus. Although normally fluent, Collins is halting on this subject, saying he is personally "intensely uncomfortable with abortion as a solution to anything." He does not advocate changing the law and says he is "very careful" to ensure that his personal feelings do not affect his political stance.

He volunteers that his views stem from his belief in "a personal God." Humans have an innate sense of right and wrong that "doesn't arise particularly well" from evolutionary theory, he argues. And he admits his own "inability, scientifically, to be able to perceive a precise moment at which life begins other than the moment of conception." Together these ideas lead to his having "some concerns" about whether genetic testing and abortion will be used to prevent conditions that are less than disastrous, such as a predisposition to obesity.

The recent movie *Gattaca* thrust before the public eye the prospect that genetic research will in the near future allow the engineering of specific desirable traits into babies. Collins thinks it is "premature to start wringing our hands" about the prospect of genetic enhancement. But he states, "I personally think that it is a path we should not go down, not now and maybe not for a very long time, if ever."

Researchers and academics familiar with Collins's work agree that he has separated his private religious views from his professional life. Paul Root Wolpe, a sociologist at the University of Pennsylvania, states that "[Collins's] history has shown no influence of religious

beliefs on his work other than a generalized sensitivity to ethics issues in genetics." Leon E. Rosenberg of Bristol-Myers Squibb, a former mentor, says that "the fact that he wears his Christianity on his sleeve is the best safeguard against any potential conflict."

Despite the general approbation, Collins is not entirely without critics. John C. Fletcher, former director of the Center for Biomedical Ethics of the University of Virginia and an Episcopalian minister before he left the church, faults Collins for not pushing to remove the current ban on using federal funds for human embryo research. Research on early embryos could lead to better treatments for pediatric cancers, Fletcher argues.

In 1996 Collins endured what he calls "the most painful experience of my professional career." A "very impressive" graduate student of his falsified experimental results relating to leukemia that had been published in five papers with Collins and others as co-authors. After Collins confronted him with a dossier of evidence, the student made a full confession. But Collins thinks his feelings of astonishment and betrayal "will never fade."

The fraud was detected by an eagle-eyed reviewer, who noticed that some photographs of electrophoresis gels that appeared in a manuscript were copied. As a result, Collins says that when someone displays a film at a meeting, "instinctively now I am surveying it to see if there is a hint that something has been manipulated." Collins remarks that since the fraud became public, a "daunting" number of scientists have contacted him to describe similar experiences of their own.

Collins still runs his own laboratory, and he continues to press a "very sharp" policy agenda. These involvements keep him busy, but he will soon spend a month with his daughter Margaret, a physician, in a missionary hospital in Nigeria. During his last visit, almost 10 years ago, he saved a man's life in a dramatic do-or-die surgery conducted with only the most basic instruments. These expeditions, to Collins, are an expression of his faith. But they are something else as well, he adds: "It seemed like it would be a wonderful thing to do with your kid."

—Tim Beardsley in Washington, D.C.

REGULATORY POLICY

PLANT MATTERS

How do you regulate an herb?

If Harlan Page Hubbard were alive, he might be the president of a dietary supplements company. In the late 19th century Hubbard sold Lydia E. Pinkham's Vegetable Compound for kidney and sexual problems. The renowned huckster is remembered each year by national consumer and health organizations who confer a "Hubbard"—a statuette clutching a fresh lemon—for the "most misleading, unfair and irresponsible advertising of the past 12 months."

Appropriately enough, one of this year's winners was a product that Hubbard might have peddled alongside his Lydia Pinkham elixir. Ginkai, an extract of the herb ginkgo, received its lemon for advertising and labeling claims that someone ingesting the product will have a better memory. Whereas some studies have shown that ginkgo improves mental functioning in people with dementia, none has proved that it serves as a brain tonic for the healthy.

The nominators for the Hubbards could have picked any one of hundreds of herbal products that have distorted claims. Unlike homeopathy and touch therapy, herbs are one of the few areas of alternative medicine that might have some grounding in science. But they have yet to transcend the status of folk nostrums because of exaggerated assertions about how they affect everything from vision to the common cold.

A presidential panel—the Commission on Dietary Supplement Labels (CDSL)—stepped into the mire in late November when it urged the Food and Drug Administration to establish a committee to review applications for herbs to be classified as nonprescription, or over-the-counter (OTC), drugs. Companies would have to show proof of safety and effectiveness to elevate the status of their herbal products to full-fledged drugs. Then they would be able to market their wares with specific government-sanctioned therapeutic claims.

Such labeling would substitute for the vague and sometimes misleading lan-

guage that currently appears on herb packaging. Although the FDA already has the statutory authority to conduct such reviews, CDSL noted in its report that the agency has taken years to decide on existing OTC applications for two herbs: valerian and ginger. In guiding the agency, the commission suggested that it examine the formal mechanisms that exist in other countries for approval of botanicals as drugs.

Any review would most likely examine Germany's systematic approach to herbal regulation. From 1978 to 1994 the German Federal Health Authority's Commission E published nearly 400 monographs that included such information on marketed herbs as composition, use, interaction with other drugs, side effects and dosage.

The monographs, put together by physicians, biostatisticians, pharmacologists and toxicologists, were then used by government officials to approve these herbs mostly as nonprescription drugs. The Commission E process has allowed herbs to gain greater acceptance by the medical establishment in Germany, where OTC drugs can be put under prescription to gain reimbursement from health insurers. "Fifty percent of the total sales of herbal products in Germany are prescribed by medical doctors," comments Konstantin Keller, a government official who coordinates the activities of Commission E.

Public-advocacy health groups do not, though, universally endorse the Commission E system as a model, citing a lack of controlled studies and an overreliance on historical evidence. "Some of the research is based on proprietary studies by manufacturers, not peer-reviewed research," says Bruce Silverglade, director of legal affairs at the Center for Science in the Public Interest, a nutrition public-interest group based in Washington, D.C. "It's not a good example of systematic scientific research." The investigations that underlie the monographs are not referenced, although similar monographs by the World Health Organization and other groups do contain citations.

Whether herbs can pass regulatory muster in the U.S. remains unclear, given skepticism about the quality of research. "My impression is that existing monographs don't rely on a controlled-trial database," notes Robert Temple,

associate director for medical policy at the FDA's Center for Drug Evaluation and Research. The interest in the antidepressant herb St. John's wort also underscores the problem. With a Commission E seal of approval, St. John's wort (*Hypericum perforatum*) is purchased in Germany as an antidepressant more than Prozac is. Unlike many other herbs, its use has the support of numerous controlled studies.

Nevertheless, the National Institutes of Health decided recently to fund a comprehensive three-year investigation of the herb to fill in holes in available research. While doing so, the NIH cited flaws in existing studies that included



CLAIMS PILE UP
for herbal products that are sold as dietary supplements.

BETH PHILLIPS

the short duration of testing, inadequate criteria for patient selection and a failure to develop standardized dosages.

The Center for Science in the Public Interest has called for a more rigorous approach than a Commission E-like system. It wants herbal preparations to be subject to review by the FDA, including, in some cases, a requirement for clinical trials. The compounds would then be classified as either prescription or OTC drugs. The dietary-supplement industry would pay for safety and efficacy trials.

But the industry quakes at suggestions that it be held to pharmaceutical-level standards. The Dietary Supplement Health and Education Act of 1994 (DSHEA) came about because of concerns in the industry that the FDA was cracking down on manufacturers of botanical remedies and vitamins. DSHEA removed herbs and other dietary sup-

plements, including vitamins and minerals, from the FDA's regulatory power to demand that supplement makers prove the safety of their products. Under DSHEA, the firms cannot make specific health or therapeutic claims, but the law does allow them to make assertions about how a product helps the "structure or function" of the body.

Manufacturers have interpreted this provision of the law liberally: "Clinically Proven to Improve Memory and Concentration," reads the label on the Ginkai package. Even if some herbs were to gain approval as over-the-counter drugs, as CDSL recommended, the manufacturers could still invoke DSHEA to market products with claims about improved memory, vision or energy. Nominators for the Hubbard awards will not have to worry about a dearth of candidates in years to come. —Gary Stix

OPTICS

LET THERE BE NO LIGHT

Artificial "crystals" now block near-optical frequencies

Semiconductors have an extremely useful feature: electrons in those materials can exist only at certain energy levels that are separated by forbidden territory called an electronic bandgap. Tinkering with this property enables engineers to tailor the electrical characteristics of transistors made from silicon and other semiconductors and hence optimize them for use in computer chips. Materials with a comparable

property with respect to light—that is, a substance with a "photonic bandgap"—might prove similarly useful. During the past several years, researchers have made such devices that worked at microwave frequencies. But now scientists at the Massachusetts Institute of Technology have succeeded in fabricating a structure that definitively works at near-visible light, paving the way for possible uses in lasers, fiber-optic communications and other applications.

The M.I.T. structure is deceptively simple: it's basically a tiny ridge of silicon with microscopic holes drilled in a row along the strip's length. The key, though, is that the holes are spaced at a regular interval that is on the same scale as the wavelength of visible light—that is, less than a millionth of a meter. At such dimensions, the holes block light traveling through the ridge; a tighter spacing of the holes would block light of even shorter wavelengths.

The concept of fabricating "crystals" with photonic bandgaps was first proposed in the late 1980s by Eli Yablonovitch, an electrical engineer at the University of California at Los Angeles. But Yablonovitch initially worked with microwaves because they require structures that have much larger periodic spacings (on the order of centimeters)—relatively easy to achieve using commonplace machine-shop technology. To block near-visible light, which has a much smaller wavelength than microwaves, the M.I.T. researchers had to resort to exotic fabrication techniques, including the use of

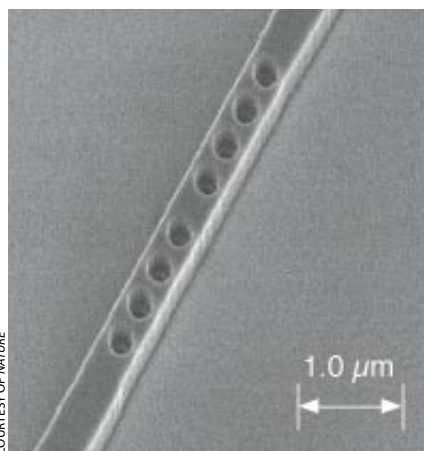
a beam of electrons for microlithography. Says Yablonovitch, "I was very confident that the same effects shown in my work at microwave frequencies would occur [theoretically] with optical frequencies, but the M.I.T. work verified this experimentally."

A valuable characteristic of the M.I.T. structure is that it allows light of only a particular wavelength within the bandgap. The researchers accomplished this feat by placing a "defect" in the "crystal": a slightly larger distance was used to space two adjacent holes in the center of the ridge. This minute irregularity makes the structure act as an extremely selective filter by altering the pattern in which light traveling through the ridge bounces off the holes, permitting just infrared light of a particular wavelength to get through. The different spacing also circumscribes a minuscule "box" that might one day be developed into a tiny, efficient light source such as a laser. "It's by far the smallest optical cavity to date," asserts James S. Foresi, one of the M.I.T. investigators on the project.

A laser, though, requires both a material that emits light and a supply of energy to make that happen. Silicon, unlike other semiconductors such as gallium arsenide, is a terrible source of light. (The M.I.T. researchers, who began their work with visions of silicon chips containing both optical and electronic circuitry working together, have been trying to improve the material's luminescence by adding erbium.) And the M.I.T. ridge rests on a glass base through which electricity will not flow, making it difficult to power any such device.

A more promising application might be as a filter for fiber-optic communications, Foresi says. The structure could separate the different light signals of various wavelengths that are crammed into the same optical fiber. A photonic-bandgap filter for such purposes would be much smaller and more practical than the comparable glass waveguide device currently being used, Foresi predicts.

Whatever the application, the microscopic size of the structure, though ideal for blocking light, might end up working against near-term commercialization. "You have to fabricate these tiny devices with tremendous accuracy," notes Thomas F. Krauss, an electrical engineer at the University of Glasgow. Consequently, Krauss contends that the technology is not yet feasible given the current fabrication techniques being used in industry. —Alden M. Hayashi



TINY HOLES
etched in a silicon ridge filter light.

NATURAL-BORN GUINEA PIGS

A start-up discovers genes for tremor and psoriasis in the DNA of inbred Icelanders

To build a life among the glaciers and volcanoes of Iceland takes a special breed of people. Not just figuratively, either: the 270,000 citizens of this island nation, a great majority of them descended from seventh-century Viking settlers, form one of the most inbred populations in the world. Now one of Iceland's prodigal sons has returned to pan that shallow gene pool for nuggets of DNA that cause disease. Less than 18 months after founding a company in Reykjavik to do just that, Kári Stefánsson and his colleagues at deCODE genetics located two genes that had eluded researchers for years. His group has nearly pinpointed other major disease-causing genes as well, he says. If Stefánsson has his way, Iceland-

ers will one day receive drugs developed from these discoveries for free.

That may sound altruistic—not to say naïve—for a businessman, but Stefánsson was not a businessman until 1996, when he quit a comfortable position as a professor of neurology at Harvard University. Genes made him do it, he declares. “Despite my dislike of the long winter nights, life in Iceland is the experience I was born to live—it fits my genetic background.” More compelling even than his own genes was the opportunity of mining his compatriots’. “If you think of genetics as the attempt to understand the flow of information from one generation to the next,” he says, Iceland seems the ideal place to trace that flow, for three reasons.

First, Icelanders are more genetically homogeneous than most other industrial societies, thanks to 1,100 years of solitude and a 14th-century plague that thinned the herd of potential mates. The lower level of natural variation should make it much easier to identify the genes that diseased family members carry but that healthy ones lack.

Inbreeding often seems to produce a fascination with genealogy, and Iceland's second gift to genetic research is its meticulous records of who begot whom. From its epic sagas, centuries of church records and libraries of genealogies, “we have been able to create a computer database containing the genealogy of the entire nation,” Stefánsson boasts.

deCODE is lobbying Iceland's Parliament to allow the company to supplement its family trees with medical records gathered from the national health service. Identifying names and numbers would be encrypted, Stefánsson hastens to point out, to protect patients' privacy. The decryption keys would be held by local clinics, not by a central authority, to be doubly safe.

Proposing a national genomic database might incite riots in some countries. But the third reason Iceland attracted him is that its near-universal literacy has made Icelanders scientifically sophisticated,

Stefánsson says. He has satisfied most of his critics by pledging that deCODE will license the genes that it discovers (all of which it intends to patent) to drugmakers only if they agree to provide medicines developed as a result to all Icelanders without charge.

That is a remarkable promise, but so far it is also an empty one: deCODE has yet to find any pharmaceutical partners. It has, however, mapped the location of the first genes ever linked to two globally widespread disorders. One of the genes, when mutated, appears to cause about 80 percent of the cases of familial essential tremor, a degenerative disease that causes shaking of the arms and head. A second project homed in on one of several genes that together cause psoriasis, a skin disease. Both projects took less than six months—a powerful proof of the principle behind deCODE's strategy, Stefánsson claims.

It could also be luck. deCODE is now working on more complex ailments that will test its technique. So far things look good. “We are hot on the trail of a major gene for multiple sclerosis,” Stefánsson confides. “We hope we will have an announcement to make by Christmas [of 1997].” If so, it will have been just the first of many nice presents for the world from the frozen North.

—W. Wayt Gibbs in San Francisco

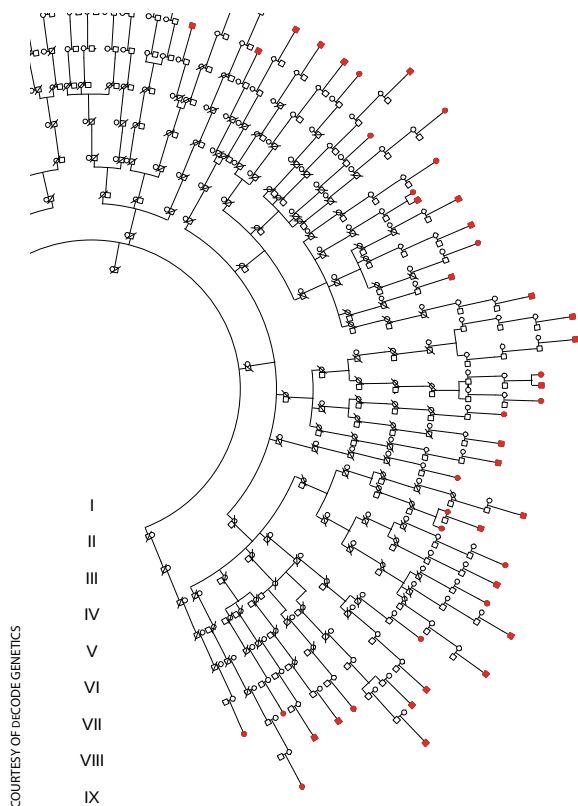
CHIP FABRICATION

FASTER, SMALLER, FLATTER

“Retro” manufacturing process keeps computer chips on the level

Karey Holland remembers her reaction one day in 1984 when a colleague at IBM recommended that she use what seemed for all the world like a scrub pad and a scouring liquid for one of the critical steps in processing the silicon wafers that contained the next-generation memory chips. The idea of exposing the wafer surface to billions of abrasive particles did not sit well with her. “You're not going to put that dirt on my wafer,” she protested.

Fourteen years later Holland makes her living by directing the development of machines that use the same technique to polish submicron layers off the sur-



COURTESY OF DECODE GENETICS

ICELANDIC FAMILY TREE,
showing asthmatic members as dark squares, helps to pin down the location of genes that cause the disease.

face of wafers. Her first reaction matched that of other engineers who thought that chemical-mechanical polishing (CMP) would prove anathema to semiconductor factories, where beams of charged ions are standard issue in fashioning the logic circuits for Pentium processors. CMP, in contrast, recalls nothing so much as technology with roots in the preindustrial era. It gave pause to the high-tech fabricators who were not initially enamored of what appeared to be a simple finishing technique. "People were repelled by the idea because it looks a lot like the polishing of glass lenses," says Frank B. Kaufman, who is CMP engineering fellow at Cabot Corporation, a supplier of CMP materials.

Making a chip surface flat—"planarization" is the term of art—is needed to stack up as many as seven layers of wiring that connect the logic circuits in the most advanced microprocessors. After two or three layers are set down, the chip surface begins to look like the skyline of a major metropolis, unless it is planarized. But lithographic machines

that pattern circuits cannot focus light down into the submicron-size valleys. So chip fabricators planarize the insulating layer at each level before laying down the metal interconnections. Otherwise, the metal-conducting material tends to aggregate in the dips while thinning at the peaks.

CMP works by covering a chip with an alkaline slurry composed of billions of silica particles that polish off a few tenths of microns from the top of the chip when pressure is applied by a porous polyurethane pad. The polishing action is enhanced by the inclusion in the slurry of alkaline chemicals that soften the surface.

The deployment of CMP marks one of the few success stories for Sematech, the U.S. industry consortium, says G. Dan Hutcheson, president of VLSI Research, a market analysis firm. Sematech helped Westech (now known as IPEC) to become established as the leading CMP supplier. CMP has become the second fastest-growing area of semiconductor equipment manufacturing—expand-

ing from a market of \$9.6 million in 1992 to an estimated \$515 million this year, according to VLSI Research. Using CMP to build stacks of wiring helped U.S. equipment manufacturers regain an advantage over foreign competition in the early 1990s in making advanced microprocessors. "More than any other technology, CMP gave the U.S. global leadership in logic," Hutcheson says. The CMP process will also emerge as an enabling technology for the next generation of chip wiring, which will use copper instead of aluminum.

An electroplating machine can deposit copper into tiny trenches carved into the silicon dioxide. CMP then polishes away the metal coated on the surface, leaving only the plated channels exposed. The technique can help make copper wiring practical in high-performance microprocessors. Like CMP, electroplating also has pre-20th-century antecedents. It serves as another instance in which retro-tech now contributes to advances in the loftiest spheres of high technology. —Gary Stix

SOLID-STATE DEVICES

IS THE END IN SIGHT?

*Promise and limits
of nanotransistors*

Fifty nanometers—50 billionths of a meter—may be the semiconductor industry's Rubicon. At this dimension, theorists have suggested that quantum-mechanical effects may begin to wreak havoc with the reliable functioning of transistors built from the dominant chip technology—the metal-oxide semiconductor (MOS).

A recent announcement by Bell Laboratories, the development arm of Lucent Technologies, brought both good and bad news about the feasibility of fabricating chips near these dimensions. Researchers there crafted what they called the "world's smallest practical transistor." On this experimental "nanotransistor," the gate—a segment of silicon and metal that turns the transistor off and on—measured only 60 nanometers across, or about 180 atoms wide.

The transistor, smaller by a factor of four than the tiniest transistors in today's chips, demonstrated that the shrinking of chips to this size could continue to bring benefits, such as higher speeds and lower power consumption, that have

driven the electronics revolution for the past 50 years. Current flow and transconductance—a measure of the ability to amplify a signal—were the highest ever reported for a MOS device. Power consumption ranged from $1/60$ to $1/160$ that of current transistors. To make the transistor, the Bell Labs team used electron beams to pattern chip circuits.

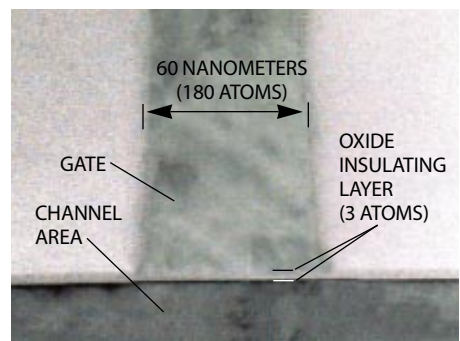
At the same time, the investigators noted other phenomena that hint that the end of the MOS era may come several chip generations from now, perhaps around the year 2010. The transistor exhibited an unwanted effect of electrons "tunneling" through the three-atom-thick (1.2 nanometers) silicon dioxide insulator layer. The insulator separates the gate from an underlying conductive "channel" of silicon doped with impurity atoms. Although tunneling did not disrupt normal current flow in the channel, Steven Hillenius, head of the device research department in the Bell Labs Silicon Electronics Research Laboratory, says it has yet to be determined whether the phenomenon might degrade the electrical properties of the oxide over time.

Even if transistors with 60-nanometer features become feasible in 2010, the generation after may not. When researchers made the insulating layer any thinner than 1.2 nano-

meters, current flow in the channel began to drop. Conventionally, making the oxide insulating layer thinner allows the voltage applied to the gate to produce a stronger electrical field, which causes more current to flow through the channel.

Hillenius's team has not ascertained why current lessened. But he postulates that quantum-mechanical effects from electrons in the gate might be causing scattering of the electrons in the channel, which could diminish current. "This could be the first of the last transistors," Hillenius muses. "Fifty years after we made the first transistor we could be reaching the end of an era."

—Gary Stix



THREE ATOMS THICK
is the size of the insulating layer
on this nanotransistor.

LUCENT TECHNOLOGIES, BELL LABORATORIES

Is Microsoft a Natural Monopoly?

The concept of a “natural monopoly” was defined in 1974 by Richard Posner, an economist who studied regulated monopolies, such as water, power, telephone and cable television companies. The government tolerated monopolies as long as it could regulate them, and justifying them as natural somehow made them acceptable in a free-enterprise system. A natural monopoly is allowed when demand is most economically and efficiently satisfied by a single producer and where competition results in duplication and wasted investment and thus fails to operate as a regulatory mechanism.

Big words, but what do they mean? How can they be applied in the modern, digital economy where dominant-market-share companies such as Intel and Microsoft are replacing the old natural monopolies such as Standard Oil and AT&T? The Department of Justice must answer these questions in the next several months as it addresses the lawsuits against Microsoft.

In the old, prewired economy, the argument in favor of a natural monopoly stood on two pillars:

1. Consumers get a better deal (price) because the natural monopoly firm reduces overhead—economies of scale derive from elimination of competition and, often, with government help. The Rural Electrification Administration is an example. Power companies were given a franchise in exchange for spreading power lines to farms and countrysides.

2. Capitalists get a better deal (lower investment, higher return) because competition has been removed. Zero competition is in a sense a way to subsidize industry so it can invest in infrastructure instead of marketing and sales. Covering the U.S. with power lines, cable TV wire and telephone exchanges costs billions. It is difficult to achieve economies of scale until the entire infrastructure is in place—hence the need to protect the risk takers with a monopoly.

From the point of view of an 1880s legislator, water, power, telephone and railway systems seemed “natural” because they provided benefits for everyone. They were for the common good.

Now the rules have changed, producing what I call a friction-free economy. Here economies of physical scale are no longer as important as market share. (That leads to the law of increasing returns, whereby value goes up as the number of customers increases.) Reducing the amount of technological duplication and other “wasted” investment is contrary to chaos in a friction-free economy, because chaos generates innovation and opportunity. Emergent behavior drives new businesses and makes possible rapid progress. So although duplicate investment may seem like a waste, it is really a necessary evil.

Our two pillars begin to crumble under the rules of the new economy. In-



stead of justifying the common good, a natural monopoly hinders its growth. Here is the friction-free-economy interpretation of the two pillars:

1. Consumers get a better deal (price) because diversity and duplication of products relentlessly reduce prices and improve quality. For example, mass customization and greater personalization are possible because of competition in an unregulated environment. This creates consumer value. Microsoft has to keep its prices low because, regardless of its size, a new innovation or competition from much bigger companies such as IBM could suddenly reverse its fortunes. If it wasn't worried about competition from Netscape, it wouldn't be playing rough in the browser war.

2. Capitalists get a better deal (lower investment, higher return) because competition is the engine that creates huge value. Stock value in regulated monopolies, such as the old AT&T, never went

anywhere. Stocks of the new regional telecommunications companies, for instance, have made capitalists ever richer. In short, capitalism loves the chaos of emergent behavior. Accordingly, chaos is attracting more investment in the friction-free economy than ever generated by the old economy that created regulated monopolies. While some win and some lose, the friction-free economy rewards “unnatural risk” via investments in innovative start-ups and fast competitors. Thus, the need to protect the risk takers with a monopoly has been replaced by the need to caution overzealous investors who believe the Nasdaq will rise forever. That's a problem most societies would gladly embrace.

One can argue that Microsoft has an unnatural monopoly because of its huge installed base, which it obtained by grabbing market share. But that base can also rapidly reduce the firm to rubble. Supplanting railroads, water systems and telephone infrastructure in the industrial age was difficult, but replacing customer loyalty and an installed base is not so costly in the friction-free economy. Netscape demonstrated this proposition by giving away its browser and rapidly ascending as a “competitor” to Microsoft in one arena.

Instead of continuing to innovate and beating Microsoft to the punch, however, Netscape has fallen back on industrial-age techniques of litigation and complaining to the government. Microsoft must be forced to correct some of its more egregious acts of persuasion, but in the long run, litigation won't work. Instead Netscape needs to return to its original strategy—that is, to innovate.

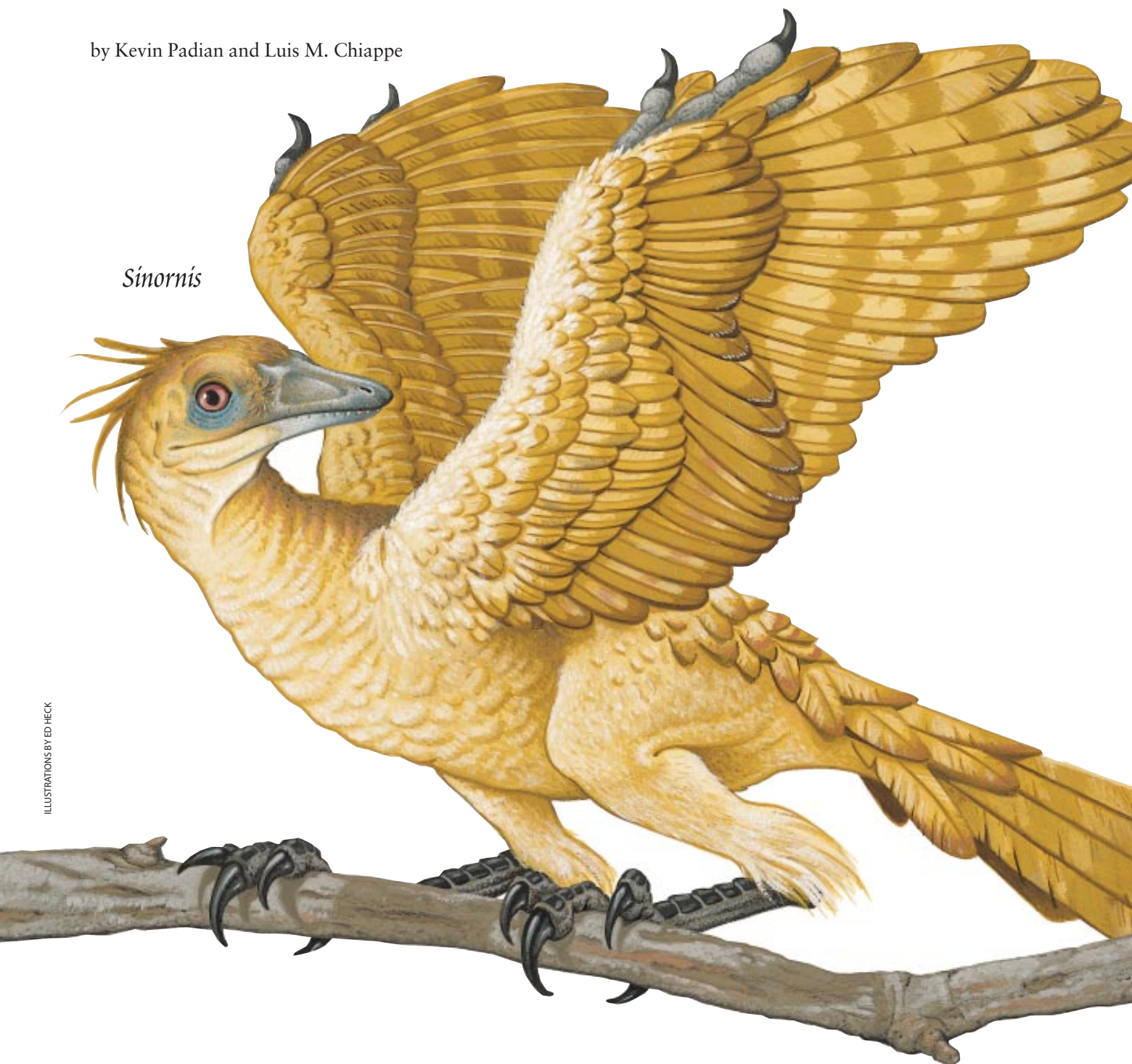
The friction-free economy is replacing the traditional economy of supply and demand, and increasing returns stemming from positive feedback are supplanting the concept of a natural monopoly. Microsoft is just a recent example of a positive-feedback monopoly. Until the Department of Justice rules against such monopolies, the government should keep its hands off Microsoft and let Intel, Sun, Netscape and Microsoft battle it out to the bitter end. The department must make sure everyone plays by the rules. But as long as the rules are followed, increasing returns are just as valid a reason for allowing a monopoly as the concept of a natural monopoly was 100 years ago. —Ted Lewis

The Origin of Birds and Their Flight

Anatomical and aerodynamic analyses of fossils and living birds show that birds evolved from small, predatory dinosaurs that lived on the ground

by Kevin Padian and Luis M. Chiappe

Sinornis



ILLUSTRATIONS BY ED HECK

Until recently, the origin of birds was one of the great mysteries of biology. Birds are dramatically different from all other living creatures. Feathers, toothless beaks, hollow bones, perching feet, wishbones, deep breastbones and stumpy tailbones are only part of the combination of skeletal features that no other living animal has in common with them. How birds evolved feathers and flight was even more imponderable.

In the past 20 years, however, new fossil discoveries and new research methods have enabled paleontologists to determine that birds descend from ground-dwelling, meat-eating dinosaurs of the group known as theropods. The work has also offered a picture of how the earliest birds took to the air.

Scientists have speculated on the evolutionary history of birds since shortly after Charles Darwin set out his theory of evolution in *On the Origin of Species*. In 1860, the year after the publication of Darwin's treatise, a solitary feather of a bird was found in Bavarian limestone deposits dating to about 150 million years ago (just before the Jurassic period gave way to the Cretaceous). The next year a skeleton of an animal that had birdlike wings and feathers—but a very unbirdlike long, bony tail and toothed jaw—turned up in the same region. These finds became the first two specimens of the blue jay-size *Archaeopteryx lithographica*, the most archaic, or basal, known member of the birds [see “*Archaeopteryx*,” by Peter Wellnhofer; SCIENTIFIC AMERICAN, May 1990].

Archaeopteryx's skeletal anatomy provides clear evidence that birds descend from a dinosaurian ancestor, but in 1861 scientists were not yet in a position to make that connection. A few years later, though, Thomas Henry Huxley, Darwin's staunch defender, became the first person to connect birds to dinosaurs. Comparing the hind limbs of *Megalosaurus*, a giant theropod, with those of the ostrich, he noted 35 features that the two groups shared but that did not occur as a suite in any other animal. He concluded that birds and theropods could be closely related, although whether he thought birds were cousins of theropods or were descended from them is not known.

Huxley presented his results to the Geological Society of London in 1870, but paleontologist Harry Govier Seeley contested Huxley's assertion of kinship between theropods and birds. Seeley suggested that the hind limbs of the ostrich and *Megalosaurus* might look similar just because both animals were large and bipedal and used their hind limbs in similar ways. Besides, dinosaurs were even larger than ostriches, and none of them could fly; how, then, could flying birds have evolved from a dinosaur?

The mystery of the origin of birds gained renewed atten-

tion about half a century later. In 1916 Gerhard Heilmann, a medical doctor with a penchant for paleontology, published (in Danish) a brilliant book that in 1926 was translated into English as *The Origin of Birds*. Heilmann showed that birds were anatomically more similar to theropod dinosaurs than to any other fossil group but for one inescapable discrepancy: theropods apparently lacked clavicles, the two collarbones that are fused into a wishbone in birds. Because other reptiles had clavicles, Heilmann inferred that theropods had lost them. To him, this loss meant birds could not have evolved from theropods, because he was convinced (mistakenly, as it turns out) that a feature lost during evolution could not be regained. Birds, he asserted, must have evolved from a more archaic reptilian group that had clavicles. Like Seeley before him, Heilmann concluded that the similarities between birds and dinosaurs must simply reflect the fact that both groups were bipedal.

Heilmann's conclusions influenced thinking for a long time, even though new information told a different story. Two separate findings indicated that theropods did, in fact, have clavicles. In 1924 a published anatomical drawing of the bizarre, parrot-headed theropod *Oviraptor* clearly showed a wish-

Iberomesornis



Eoalulavis



EARLY BIRDS living more than 100 million years ago looked quite different from birds of today. For instance, as these artist's reconstructions demonstrate, some retained the clawed fingers and toothed jaw characteristic of nonavian dinosaurs. Fossils of *Sinornis* (left) were uncovered in China; those of *Iberomesornis* and *Eoalulavis* (right) in Spain. All three birds were about the size of a sparrow. *Eoalulavis* sported the first known alula, or “thumb wing,” an adaptation that helps today's birds navigate through the air at slow speeds.

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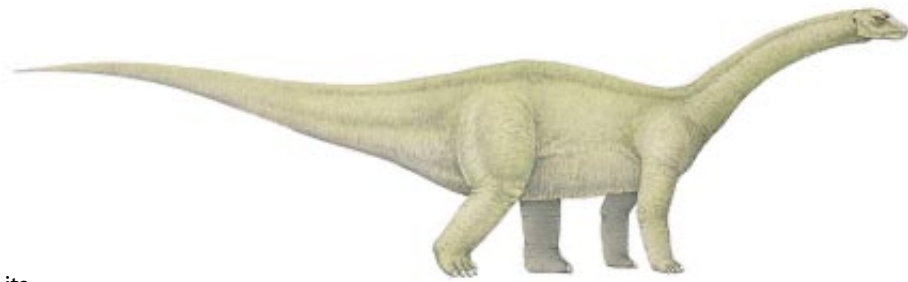
Tracking the Dinosaur Lineage Leading to Birds

The family tree at the right traces the ancestry of birds back to their early dinosaurian ancestors. This tree, otherwise known as a cladogram, is the product of today's gold standard for analyzing the evolutionary relations among animals—a method called cladistics.

Practitioners of cladistics determine the evolutionary history of a group of animals by examining certain kinds of traits. During evolution, some animal will display a new, genetically determined trait that will be passed to its descendants. Hence, paleontologists can conclude that two groups uniquely sharing a suite of such novel, or derived, traits are more closely related to each other than to animals lacking those traits.

Nodes, or branching points (*dots*), on a cladogram mark the emergence of a lineage possessing a new set of derived traits. In the cladogram here, the Theropoda all descend from a dinosaurian ancestor that newly possessed hollow bones and had only three functional toes. In this scheme, the theropods are still dinosaurs; they are simply a subset of the saurischian dinosaurs. Each lineage, or clade, is thus nested within a larger one (*colored rectangles*). By the same token, birds (*Aves*) are maniraptoran, tetanuran and theropod dinosaurs.

—K.P. and L.M.C.



Titanosaurus

DINOSAUR LINEAGES
THAT DID NOT LEAD
TO BIRDS

DINOSAURIA

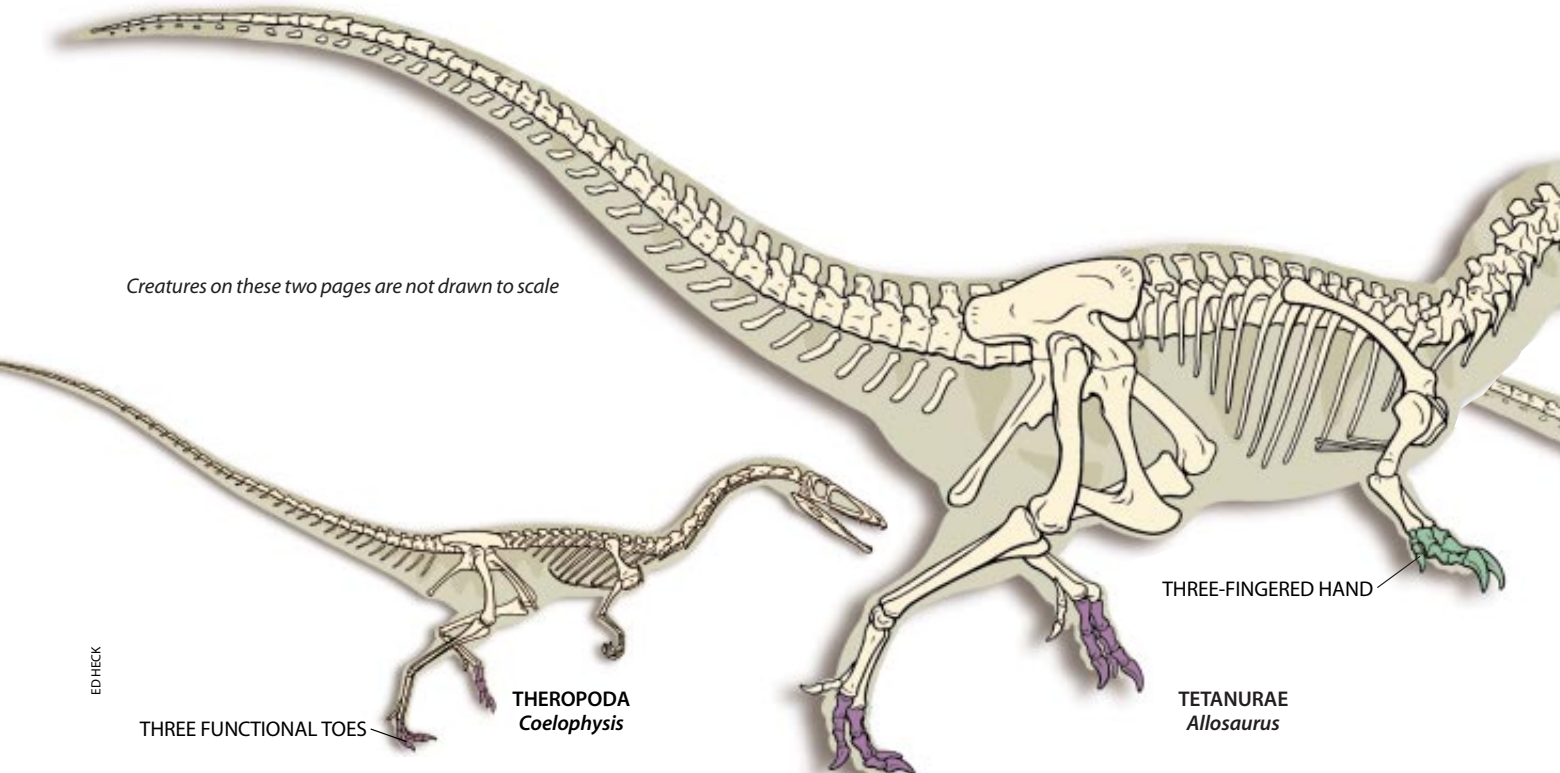
SAURISCHIA

bone, but the structure was misidentified. Then, in 1936, Charles Camp of the University of California at Berkeley found the remains of a small Early Jurassic theropod, complete with clavicles. Heilmann's fatal objection had been overcome, although few scientists recognized it. Recent studies have found clavicles in a broad spectrum of the theropods related to birds.

Finally, a century after Huxley's disputed presentation to the Geological Society of London, John H. Ostrom of Yale

University revived the idea that birds were related to theropod dinosaurs, and he proposed explicitly that birds were their direct descendants. In the late 1960s Ostrom had described the skeletal anatomy of the theropod *Deinonychus*, a vicious, sickle-clawed predator about the size of an adolescent human, which roamed in Montana some 115 million years ago (in the Early Cretaceous). In a series of papers published during the next decade, Ostrom went on to identify a collection of features that birds, including *Archaeopteryx*, shared

Creatures on these two pages are not drawn to scale



THREE FUNCTIONAL TOES

THEROPODA
Coelophysis

THREE-FINGERED HAND

TETANURAE
Allosaurus

THEROPODA Three functional toes; hollow bones

TETANURAE Three-fingered hand

MANIRAPTORA Half-moon-shaped wristbone

AVES Reversed first toe;
fewer than 26 vertebrae in tail

Coelophysis

Allosaurus

Velociraptor

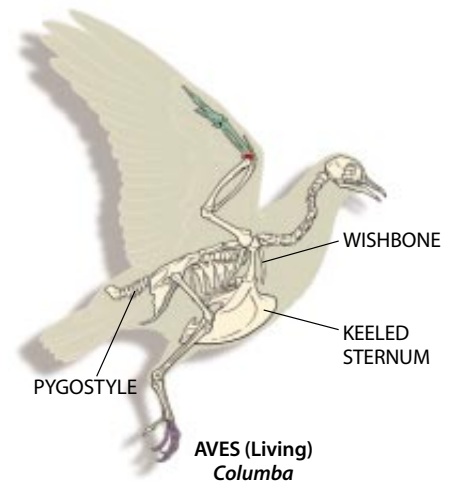
Archaeopteryx

Columba
(pigeon)

TOMO NARASHIMA

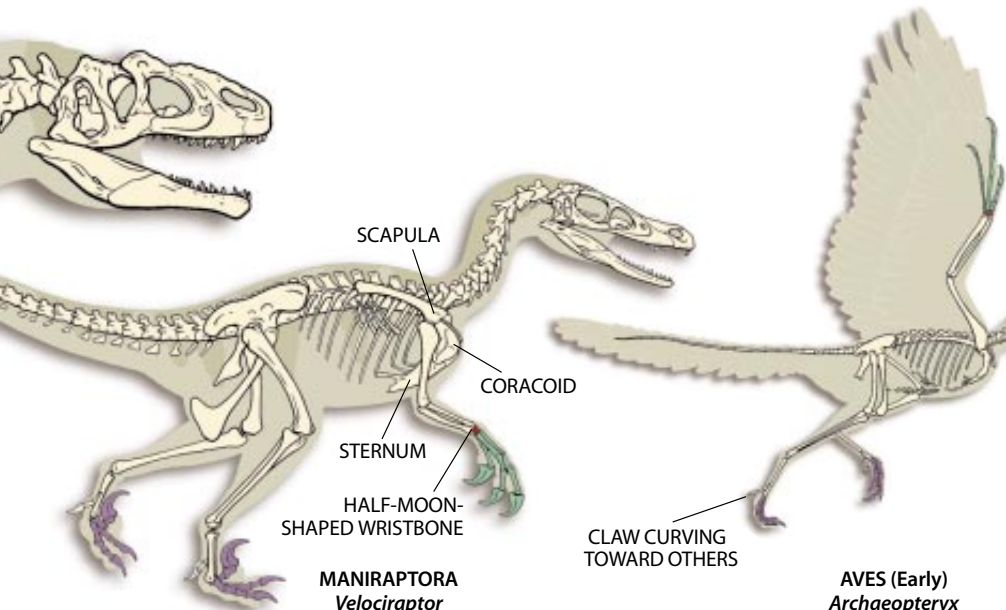
with *Deinonychus* and other theropods but not with other reptiles. On the basis of these findings, he concluded that birds are descended directly from small theropod dinosaurs.

As Ostrom was assembling his evidence for the theropod origin of birds, a new method of deciphering the relations among organisms was taking hold in natural history museums in New York City, Paris and elsewhere. This method—called phylogenetic systematics or, more commonly, cladistics—has since become the standard for comparative biology, and its use has strongly validated Ostrom's conclusions.



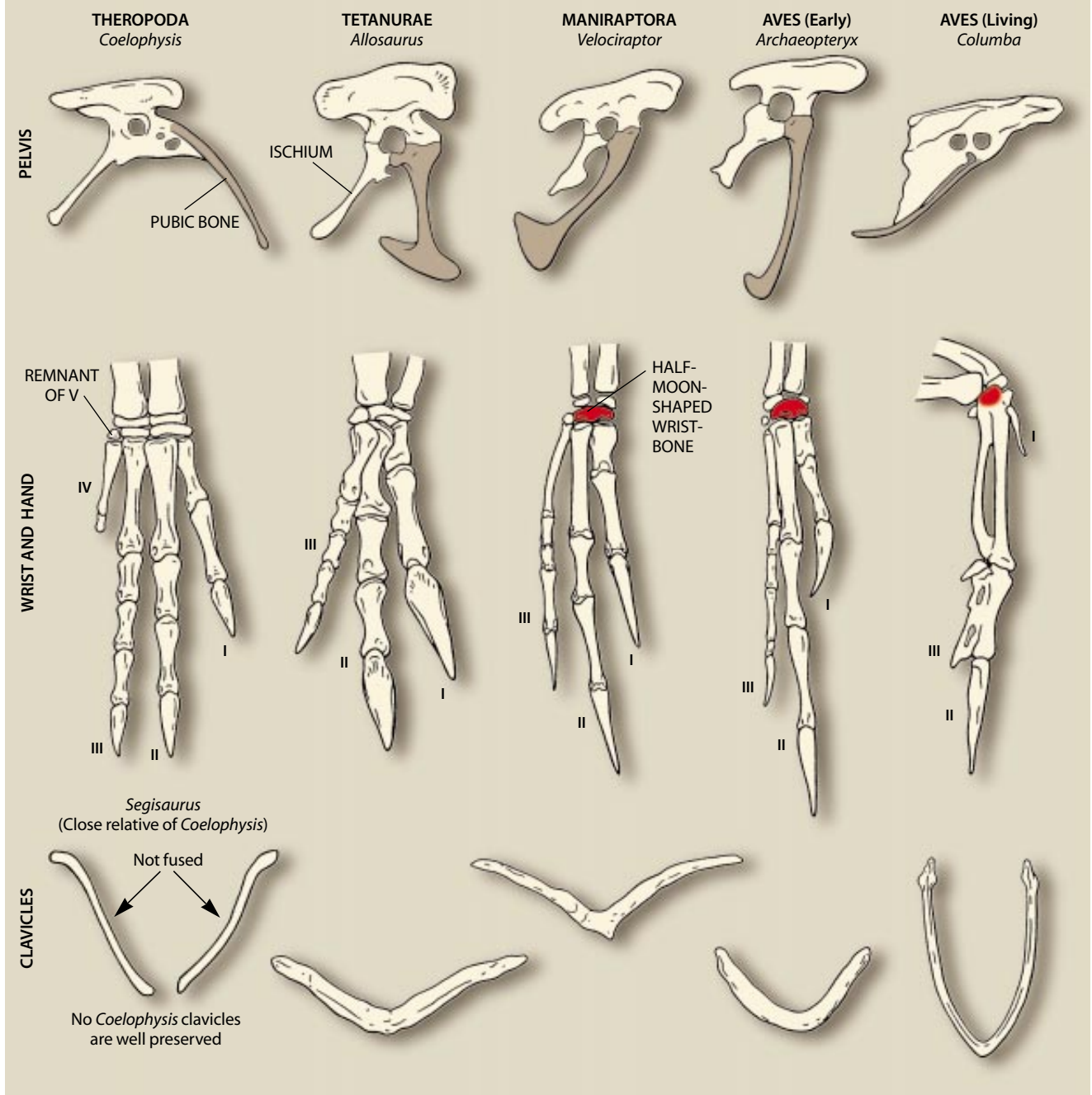
AVES (Living)
Columba

REPRESENTATIVE THEROPODS in the lineage leading to birds (Aves) display some of the features that helped investigators establish the dinosaurian origin of birds—including, in the order of their evolution, three functional toes (*purple*), a three-fingered hand (*green*) and a half-moon-shaped wristbone (*red*). *Archaeopteryx*, the oldest known bird, also shows some new traits, such as a claw on the back toe that curves toward the claws on the other toes. As later birds evolved, many features underwent change. Notably, the fingers fused together, the simple tail became a pygostyle composed of fused vertebrae, and the back toe dropped, enabling birds' feet to grasp tree limbs firmly.



MANIRAPTORA
Velociraptor

AVES (Early)
Archaeopteryx



ED HECK

COMPARISONS OF ANATOMICAL STRUCTURES not only helped to link birds to theropods, they also revealed some of the ways those features changed as dinosaurs became more birdlike and birds became more modern. In the pelvis (*side view*), the pubic bone (*brown*) initially pointed forward (toward the right), but it later shifted to be vertical or pointed backward. In the hand (*top view*), the relative proportions of the bones re-

mained quite constant through the early birds, but the wrist changed. In the maniraptoran wrist, a disklike bone took on the half-moon shape (*red*) that ultimately promoted flapping flight in birds. The wide, boomerang-shaped wishbone (fused clavicles) in tetanurans and later groups compares well with that of archaic birds, but it became thinner and formed a deeper U shape as it became more critical in flight.

Traditional methods for grouping organisms look at the similarities and differences among the animals and might exclude a species from a group solely because the species has a trait not found in other members of the group. In contrast, cladistics groups organisms based exclusively on certain kinds of shared traits that are particularly informative.

This method begins with the Darwinian precept that evolution proceeds when a new heritable trait emerges in some organism and is passed genetically to its descendants. The precept indicates that two groups of animals sharing a set of

such new, or "derived," traits are more closely related to each other than they are to groups that display only the original traits but not the derived ones. By identifying shared derived traits, practitioners of cladistics can determine the relations among the organisms they study.

The results of such analyses, which generally examine many traits, can be represented in the form of a cladogram: a treelike diagram depicting the order in which new characteristics, and new creatures, evolved [see box on preceding two pages]. Each branching point, or node, reflects the emergence

of an ancestor that founded a group having derived characteristics not present in groups that evolved earlier. This ancestor and all its descendants constitute a “clade,” or closely related group.

Ostrom did not apply cladistic methods to determine that birds evolved from small theropod dinosaurs; in the 1970s the approach was just coming into use. But about a decade later Jacques A. Gauthier, then at the University of California at Berkeley, did an extensive cladistic analysis of birds, dinosaurs and their reptilian relatives. Gauthier put Ostrom’s comparisons and many other features into a cladistic framework and confirmed that birds evolved from small theropod dinosaurs. Indeed, some of the closest relatives of birds include the sickle-clawed maniraptoran *Deinonychus* that Ostrom had so vividly described.

Today a cladogram for the lineage leading from theropods to birds shows that the clade labeled Aves (birds) consists of the ancestor of *Archaeopteryx* and all other descendants of that ancestor. This clade is a subgroup of a broader clade consisting of so-called maniraptoran theropods—itself a subgroup of the tetanuran theropods that descended from the most basal theropods. Those archaic theropods in turn evolved from nontheropod dinosaurs. The cladogram shows that birds are not only *descended* from dinosaurs, they *are* dinosaurs (and reptiles)—just as humans are mammals, even though people are as different from other mammals as birds are from other reptiles.

Early Evolutionary Steps to Birds

Gauthier’s studies and ones conducted more recently demonstrate that many features traditionally considered “birdlike” actually appeared before the advent of birds, in their preavian theropod ancestors. Many of those properties undoubtedly helped their original possessors to survive as terrestrial dinosaurs; these same traits and others were eventually used directly or were transformed to support flight and an arboreal way of life. The short length of this article does not allow us to catalogue the many dozens of details that combine to support the hypothesis that birds evolved from small theropod dinosaurs, so we will concentrate mainly on those related to the origin of flight.

The birdlike characteristics of the theropods that evolved prior to birds did not appear all at once, and some were present before the theropods themselves emerged—in the earliest dinosaurs. For instance, the immediate reptilian ancestor of dinosaurs was already bipedal and upright in its stance (that is, it basically walked like a bird), and it was small and carnivorous. Its hands, in common with those of early birds, were free for grasping (although the hand still had five digits, not the three found in all but the most basal theropods and in birds). Also, the second finger was longest—not the third, as in other reptiles.

Further, in the ancestors of dinosaurs, the ankle joint had already become hingelike, and the metatarsals, or foot bones, had become elongated. The metatarsals were held off the ground, so the immediate relatives of dinosaurs, and dinosaurs themselves, walked on their toes and put one foot in front of the other, instead of sprawling. Many of the changes in the feet are thought to have increased stride length and running speed, a property that would one day help avian theropods to fly.

The earliest theropods had hollow bones and cavities in

the skull; these adjustments lightened the skeleton. They also had a long neck and held their back horizontally, as birds do today. In the hand, digits four and five (the equivalent of the pinky and its neighbor) were already reduced in the first dinosaurs; the fifth finger was virtually gone. Soon it was completely lost, and the fourth was reduced to a nubbin. Those reduced fingers disappeared altogether in tetanuran theropods, and the remaining three (I, II, III) became fused together sometime after *Archaeopteryx* evolved.

In the first theropods, the hind limbs became more birdlike as well. They were long; the thigh was shorter than the shin, and the fibula, the bone to the side of the shinbone, was re-

Bones of Contention

Although many lines of evidence establish that birds evolved from small, terrestrial theropod dinosaurs, a few scientists remain vocally unconvinced. They have not, however, tested any alternative theory by cladistics or by any other method that objectively analyzes relationships among animals. Here is a sampling of their arguments, with some of the evidence against those assertions.

Bird and theropod hands differ: theropods retain fingers I, II and III (having lost the “pinky” and “ring finger”), but birds have fingers II, III and IV. This view of the bird hand is based on embryological research suggesting that when digits are lost from the five-fingered hand, the outer fingers (I and V) are the first to go. No one doubts that theropods retain fingers I, II and III, however, so this “law” clearly has exceptions and does not rule out retention of the first three fingers in birds. More important, the skeletal evidence belies the alleged difference in the hands of birds and nonavian theropods. The three fingers that nonavian theropods kept after losing the fourth and fifth have the same forms, proportions and connections to the wristbones as the fingers in *Archaeopteryx* and later birds [see middle row of illustration on opposite page].

Theropods appear too late to give rise to birds. Proponents of this view have noted that *Archaeopteryx* appears in the fossil record about 150 million years ago, whereas the fossil remains of various nonavian maniraptors—the closest known relatives of birds—date only to about 115 million years ago. But investigators have now uncovered bones that evidently belong to small, nonavian maniraptors and that date to the time of *Archaeopteryx*. In any case, failure to find fossils of a predicted kind does not rule out their existence in an undiscovered deposit.

The wishbone (composed of fused clavicles) of birds is not like the clavicles in theropods. This objection was reasonable when only the clavicles of early theropods had been discovered, but boomerang-shaped wishbones that look just like that of *Archaeopteryx* have now been uncovered in many theropods.

The complex lungs of birds could not have evolved from theropod lungs. This assertion cannot be supported or falsified at the moment, because no fossil lungs are preserved in the paleontological record. Also, the proponents of this argument offer no animal whose lungs could have given rise to those in birds, which are extremely complex and are unlike the lungs of any living animal.

—K.P. and L.M.C.

THEROPOD FOSSILS recently discovered in China suggest that the structures that gave rise to feathers probably predated the emergence of birds. *Sinosauropteryx* (left) sported a filamentous fringe along its back that could have consisted of precursors to feathers. And *Protarchaeopteryx* (right) bore true feathers, such as the cluster that is magnified in the top detail; the smaller detail highlights part of one feather.

duced. (In birds today the toothpicklike bone in the drumstick is all that is left of the fibula.) These dinosaurs walked on the three middle toes—the same ones modern birds use. The fifth toe was shortened and tapered, with no joints, and the first toe included a shortened metatarsal (with a small joint and a claw) that projected from the side of the second toe. The first toe was held higher than the others and had no apparent function, but it was later put to good use in birds. By the time *Archaeopteryx* appeared, that toe had rotated to lie behind the others. In later birds, it descended to become opposable to the others and eventually formed an important part of the perching foot.

More Changes

Through the course of theropod evolution, more features once thought of as strictly avian emerged. For instance, major changes occurred in the forelimb and shoulder girdle; these adjustments at first helped theropods to capture prey and later promoted flight. Notably, during theropod evolution, the arms became progressively longer, except in such giant carnivores as *Carnotaurus*, *Allosaurus* and *Tyrannosaurus*, in which the forelimbs were relatively small. The forelimb was about half the length of the hind limb in very early theropods. By the time *Archaeopteryx* appeared, the forelimb was longer than the hind limb, and it grew still more in later birds. This lengthening in the birds allowed a stronger flight stroke.

The hand became longer, too, accounting for a progressively greater proportion of the forelimb, and the wrist underwent dramatic revision in shape. Basal theropods possessed a flat wristbone (distal carpal) that overlapped the bases of the first and second palm bones (metacarpals) and fingers. In maniraptorans, though, this bone assumed a half-moon shape along the surface that contacted the arm bones. The half-moon, or semilunate, shape was very important because it allowed these animals to flex the wrist sideways in addition to up and down. They could thus fold the long hand, almost as living birds do. The longer hand could then be rotated and whipped forward suddenly to snatch prey.

In the shoulder girdle of early theropods, the scapula (shoulder blade) was long and straplike; the coracoid (which along with the scapula forms the shoulder joint) was rounded, and two separate, S-shaped clavicles connected the shoulder to the sternum, or breastbone. The scapula soon became longer and narrower; the coracoid also thinned and elongated, stretching toward the breastbone. The clavicles fused at the midline and broadened to form a boomerang-shaped wishbone. The sternum, which consisted originally of cartilage, calcified into two fused bony plates in tetanurans. Together these changes strengthened the skeleton; later this strengthening was used to reinforce the flight apparatus and support the flight muscles. The new wishbone, for instance, probably became an anchor for the muscles that moved the forelimbs, at first during foraging and then during flight.



In the pelvis, more vertebrae were added to the hip girdle, and the pubic bone (the pelvic bone that is attached in front of and below the hip socket) changed its orientation. In the first theropods, as in most other reptiles, the pubis pointed down and forward, but then it began to point straight down or backward. Ultimately, in birds more advanced than *Archaeopteryx*, it became parallel to the ischium, the pelvic bone that extends backward from below the hip socket. The benefits derived from these changes, if any, remain unknown, but the fact that these features are unique to birds and other maniraptorans shows their common origin.

Finally, the tail gradually became shorter and stiffer throughout theropod history, serving more and more as a balancing organ during running, somewhat as it does in today's road-runners. Steven M. Gatesy of Brown University has demonstrated that this transition in tail structure paralleled another change in function: the tail became less and less an anchor for the leg muscles. The pelvis took over that function, and in maniraptorans the muscle that once drew back the leg now mainly controlled the tail. In birds that followed *Archaeopteryx*, these muscles would be used to adjust the feathered tail as needed in flight.

In summary, a great many skeletal features that were once thought of as uniquely avian innovations—such as light, hollow bones, long arms, three-fingered hands with a long second finger, a wishbone, a backward-pointing pelvis, and long hind limbs with a three-toed foot—were already present in theropods before the evolution of birds. Those features generally served different uses than they did in birds and were only later co-opted for flight and other characteristically avian functions, eventually including life in the trees.

Evidence for the dinosaurian origin of birds is not confined to the skeleton. Recent discoveries of nesting sites in Mongolia and Montana reveal that some reproductive behaviors

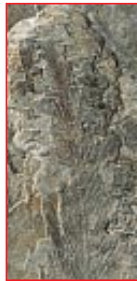


PHOTOGRAPHS BY MICK ELLISON

will depend on a fuller description of its anatomy. Nevertheless, the Chinese finds imply that, at the least, the structures that gave rise to feathers probably appeared before birds did and almost certainly before birds began to fly. Whether their original function was for insulation, display or something else cannot yet be determined.

The Beginning of Bird Flight

The origin of birds and the origin of flight are two distinct, albeit related, problems. Feathers were present for other functions before flight evolved, and *Archaeopteryx* was probably not the very first flying theropod, although at present we have no fossils of earlier flying precursors. What can we say about how flight began in bird ancestors?



Traditionally, two opposing scenarios have been put forward. The “arboreal” hypothesis holds that bird ancestors began to fly by climbing trees and gliding down from branches with the help of incipient feathers. The

height of trees provides a good starting place for launching flight, especially through gliding. As feathers became larger over time, flapping flight evolved, and birds finally became fully airborne.

This hypothesis makes intuitive sense, but certain aspects are troubling. *Archaeopteryx* and its maniraptoran cousins have no obviously arboreal adaptations, such as feet fully adapted for perching. Perhaps some of them could climb trees, but no convincing analysis has demonstrated how *Archaeopteryx* would have climbed and flown with its forelimbs, and there were no plants taller than a few meters in the environments where *Archaeopteryx* fossils have been found. Even if the animals could climb trees, this ability is not synonymous with arboreal habits or gliding ability. Most small animals, and even some goats and kangaroos, can climb trees, but that does not make them tree dwellers. Besides, *Archaeopteryx* shows no obvious features of gliders, such as a broad membrane connecting forelimbs and hind limbs.

The “cursorial” (running) hypothesis holds that small dinosaurs ran along the ground and stretched out their arms for balance as they leaped into the air after insect prey or, perhaps, to avoid predators. Even rudimentary feathers on forelimbs could have expanded the arm’s surface area to enhance lift slightly. Larger feathers could have increased lift incrementally, until sustained flight was gradually achieved. Of course, a leap into the air does not provide the acceleration produced by dropping out of a tree; an animal would have to run quite fast to take off. Still, some small terrestrial animals can achieve high speeds.

The cursorial hypothesis is strengthened by the fact that the immediate theropod ancestors of birds were terrestrial. And they had the traits needed for high liftoff speeds: they were small, active, agile, lightly built, long-legged and good runners. And because they were bipedal, their arms were free

of birds originated in nonavian dinosaurs. These theropods did not deposit a large clutch of eggs all at once, as most other reptiles do. Instead they filled a nest more gradually, laying one or two eggs at a time, perhaps over several days, as birds do. Recently skeletons of the Cretaceous theropod *Oviraptor* have been found atop nests of eggs; the dinosaurs were apparently buried while protecting the eggs in very birdlike fashion. This find is ironic because *Oviraptor*, whose name means “egg stealer,” was first thought to have been raiding the eggs of other dinosaurs, rather than protecting them. Even the structure of the eggshell in theropods shows features otherwise seen only in bird eggs. The shells consist of two layers of calcite, one prismatic (crystalline) and one spongy (more irregular and porous).

As one supposedly uniquely avian trait after another has been identified in nonavian dinosaurs, feathers have continued to stand out as a prominent feature belonging to birds alone. Some intriguing evidence, however, hints that even feathers might have predated the emergence of birds.

In 1996 and 1997 Ji Qiang and Ji Shu’an of the National Geological Museum of China published reports on two fossil animals found in Liaoning Province that date to late in the Jurassic or early in the Cretaceous. One, a turkey-size dinosaur named *Sinosauropteryx*, has fringed, filamentous structures along its backbone and on its body surface. These structures of the skin, or integument, may have been precursors to feathers. But the animal is far from a bird. It has short arms and other skeletal properties indicating that it may be related to the theropod *Compsognathus*, which is not especially close to birds or other maniraptorans.

The second creature, *Protarchaeopteryx*, apparently has short, true feathers on its body and has longer feathers attached to its tail. Preliminary observations suggest that the animal is a maniraptoran theropod. Whether it is also a bird

to evolve flapping flight, which cannot be said for other reptiles of their time.

Although our limited evidence is tantalizing, probably neither the arboreal nor the cursorial model is correct in its extreme form. More likely, the ancestors of birds used a combination of taking off from the ground and taking advantage of accessible heights (such as hills, large boulders or fallen trees). They may not have climbed trees, but they could have used every available object in their landscape to assist flight.

More central than the question of ground versus trees, however, is the evolution of a flight stroke. This stroke generates not only the lift that gliding animals obtain from moving their wings through the air (as an airfoil) but also the thrust that enables a flapping animal to move forward. (In contrast, the “organs” of lift and thrust in airplanes—the wings and jets—are separate.) In birds and bats, the hand part of the wing generates the thrust, and the rest of the wing provides the lift.

Jeremy M. V. Rayner of the University of Bristol showed in the late 1970s that the down-and-forward flight stroke of birds and bats produces a series of doughnut-shaped vortices that propel the flying animal forward. One of us (Padian) and Gauthier then demonstrated in the mid-1980s that the movement generating these vortices in birds is the same action—sideways flexion of the hand—that was already present in the maniraptorans *Deinonychus* and *Velociraptor* and in *Archaeopteryx*.

As we noted earlier, the first maniraptorans must have used this movement to grab prey. By the time *Archaeopteryx* and other birds appeared, the shoulder joint had changed its angle to point more to the side than down and backward. This alteration in the angle transformed the forelimb motion from

a prey-catching one to a flight stroke. New evidence from Argentina suggests that the shoulder girdle in the closest maniraptorans to birds (the new dinosaur *Unenlagia*) was already angled outward so as to permit this kind of stroke.

Recent work by Farish A. Jenkins, Jr., of Harvard University, George E. Goslow of Brown University and their colleagues has revealed much about the role of the wishbone in flight and about how the flight stroke is achieved. The wishbone in some living birds acts as a spacer between the shoulder girdles, one that stores energy expended during the flight stroke. In the first birds, in contrast, it probably was less elastic, and its main function may have been simply to anchor the forelimb muscles. Apparently, too, the muscle most responsible for rotating and raising the wing during the recovery stroke of flight was not yet in the modern position in *Archaeopteryx* or other very early birds. Hence, those birds were probably not particularly skilled fliers; they would have been unable to flap as quickly or as precisely as today's birds can. But it was not long—perhaps just several million years—before birds acquired the apparatus they needed for more controlled flight.

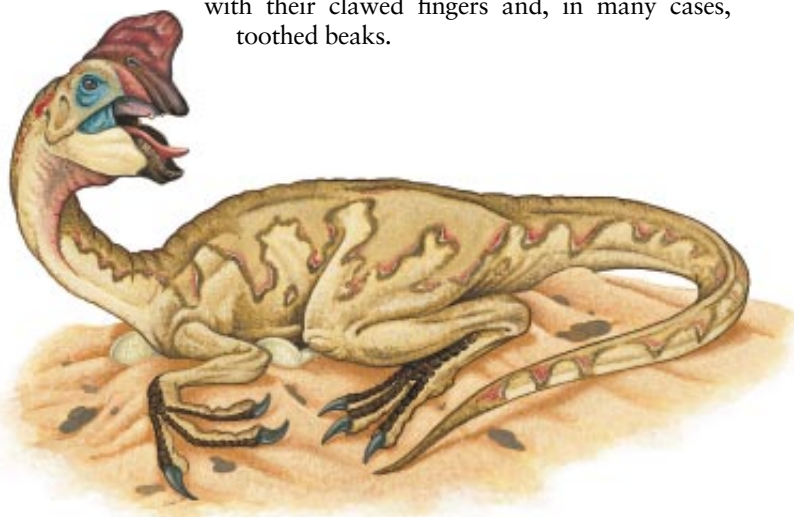
Beyond *Archaeopteryx*

More than three times as many bird fossils from the Cretaceous period have been found since 1990 than in all the rest of recorded history. These new specimens—uncovered in such places as Spain, China, Mongolia, Madagascar and Argentina—are helping paleontologists to flesh out the early evolution of the birds that followed *Archaeopteryx*, including their acquisition of an improved flying system. Analyses of these finds by one of us (Chiappe) and others have shown that birds quickly took on many different sizes, shapes and behaviors (ranging from diving to flightlessness) and diversified all through the Cretaceous period, which ended about 65 million years ago.

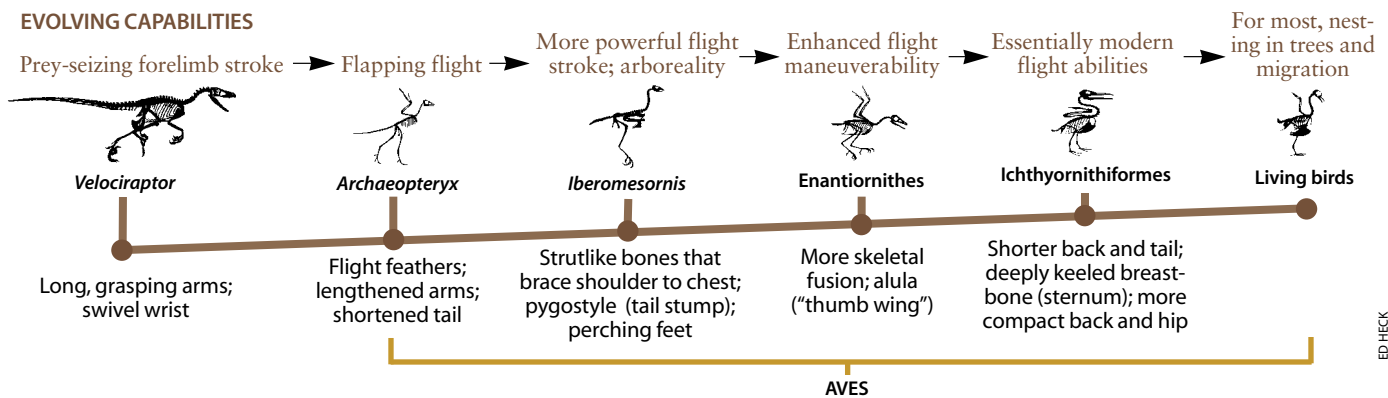
A bird-watching trek through an Early Cretaceous forest would bear little resemblance to such an outing now. These early birds might have spent much of their time in the trees and were able to perch, but there is no evidence that the first birds nested in trees, had complex songs or migrated great distances. Nor did they fledge at nearly adult size, as birds do now, or grow as rapidly as today's birds do. Scientists can only imagine what these animals looked like. Undoubtedly, however, they would have seemed very strange, with their clawed fingers and, in many cases, toothed beaks.



OVIRAPTOR, a maniraptoran theropod that evolved before birds, sat in its nest to protect its eggs (left drawing), just as the ostrich (right drawing) and other birds do today. In other words, such brooding originated before birds did. In the fossil that served as the basis for the *Oviraptor* drawing (photograph, above), the position of the claws indicates that the limbs were drawn in around the eggs (large ovals), to protect them.



EVOLVING CAPABILITIES



ED HECK

CLADOGRAM OF BIRD EVOLUTION indicates that birds (Aves) perfected their flight stroke gradually after they first appeared approximately 150 million years ago. They became ar-

boreal (able to live in trees) relatively early in their history, however. Some of the skeletal innovations that supported their emerging capabilities are listed at the bottom.

Underneath the skin, though, some skeletal features certainly became more birdlike during the Early Cretaceous and enabled birds to fly quite well. Many bones in the hand and in the hip girdle fused, providing strength to the skeleton for flight. The breastbone became broader and developed a keel down the midline of the chest for flight muscle attachment. The forearm became much longer, and the skull bones and vertebrae became lighter and more hollowed out. The tailbones became a short series of free segments ending in a fused stump (the familiar "parson's nose" or "Pope's nose" of roasted birds) that controlled the tail feathers. And the alula, or "thumb wing," a part of the bird wing essential for flight control at low speed, made its debut, as did a long first toe useful in perching.

Inasmuch as early birds could fly, they certainly had higher metabolic rates than cold-blooded reptiles; at least they were able to generate the heat and energy needed for flying without having to depend on being heated by the environment. But they might not have been as fully warm-blooded as today's birds. Their feathers, in addition to aiding flight, provided a measure of insulation—just as the precursors of feathers could have helped preserve heat and conserve energy in nonavian precursors of birds. These birds probably did not fly as far or as strongly as birds do now.

Bird-watchers traipsing through a forest roughly 50 million years later would still have found representatives of very primitive lineages of birds. Yet other birds would have been recognizable as early members of living groups. Recent research shows that at least four

major lineages of living birds—including ancient relatives of shorebirds, seabirds, loons, ducks and geese—were already thriving several million years before the end of the Cretaceous period, and new paleontological and molecular evidence suggests that forerunners of other modern birds were around as well.

Most lineages of birds that evolved during the Cretaceous died out during that period, although there is no evidence that they perished suddenly. Researchers may never know whether the birds that disappeared were outcompeted by newer forms, were killed by an environmental catastrophe or were just unable to adapt to changes in their world. There is no reasonable doubt, however, that all groups of birds, living and extinct, are descended from small, meat-eating theropod dinosaurs, as Huxley's work intimated more than a century ago. In fact, living birds are nothing less than small, feathered, short-tailed theropod dinosaurs. SA

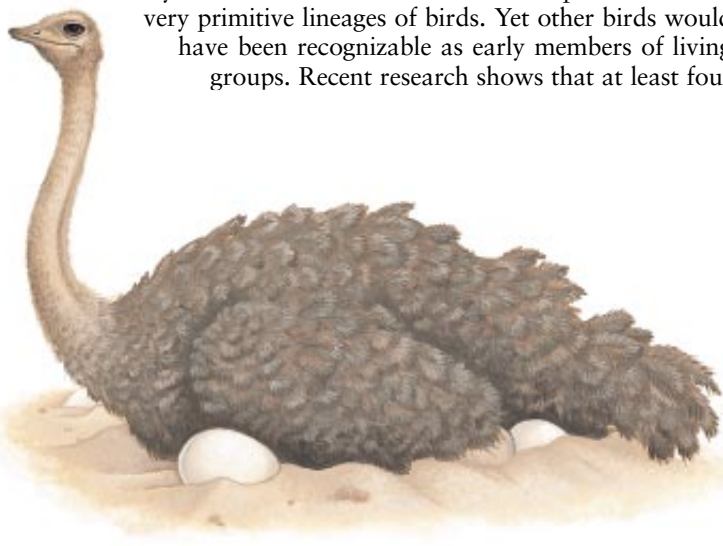
The Authors

KEVIN PADIAN and LUIS M. CHIAPPE are frequent collaborators. Padian is professor of integrative biology and curator in the Museum of Paleontology at the University of California, Berkeley. He is also president of the National Center for Science Education. Chiappe, who has extensively studied the radiation of birds during the Cretaceous period, is Chapman Fellow and research associate at the American Museum of Natural History in New York City and adjunct professor at the City University of New York.

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ILLUSTRATIONS BY ED HECK



Scientists in Black

by Jeffrey T. Richelson

During the five decades of the cold war, the U.S. spent several hundred billion dollars to design, build and operate an imposing array of advanced systems to collect intelligence or map certain militarily useful features of the earth. In space, dozens of reconnaissance satellites produced millions of images of the earth's surface, while infrared sensors on other satellites recorded missile launchings, explosions and other energetic events. In the skies, specially designed aircraft snapped reconnaissance pictures and made meteorological measurements. Undersea sonar arrays tracked the movements of submarines; surface ships mapped the sea bottom with remarkable accuracy.

The untold millions of images and perhaps quadrillions of bytes of data collected by this global array now reside in data centers, computer rooms, archives, photographic libraries and other installations scattered mostly around Washington, D.C. And although some of the data continue to have military or intelligence value, for much of the rest, time and the demise of the Soviet Union have sharply reduced their relevance.

In recent years, however, a fairly radical concept has begun taking hold, which has given new purpose to these expensively created data reservoirs. The notion being much of this information gathered for intelligence or military purposes is scientifically useful and that, moreover, it can be put to scientific use without compromising any of the intelligence or military imperatives—such as secrecy—under which it was originally collected and used.

The idea has led to the formation of a group consisting of dozens of U.S. scientists who have been granted high-level security clearances and who have been poring over portions of the data, images and records compiled by the U.S.'s far-flung intelligence apparatus. The scientists in this group, known as Medea, have been briefed on the most highly classified and advanced sensors and plat-

forms and have even been asked to advise intelligence officials on the ways in which new platforms could be designed, and existing ones operated, to address the needs of science more effectively.

Because the collaboration is only a few years old, it is too soon to declare it a success or a failure. But its mere survival for several years is noteworthy. Never before has the intelligence community worked with a group of scientists outside the government with the kind of scale, trust and intimacy that will be required if the scientists are to make the fullest use of the government data and assets. Most significantly, cooperation will require an accommodation between two cultures, those of science and intelligence, that have essentially opposite methods of handling information. In science, the unrestricted dissemination of data is accepted as being necessary for progress, whereas in intelligence, the flow of information is tightly restricted by a "need to know" policy: only those who have the proper security clearances and who cannot carry out their assigned responsibilities without certain knowledge or information are given access to it.

So far much of the work of the Medea scientists has been determining whether existing data and assets can be of use to scientists studying trends in global warming, ocean temperatures, vegetation and forest cover, the spread of deserts, the condition of the polar ice caps and similar issues in environmental science. Two scientific papers have been published to date based on intelligence data, offering the first glimpses of how unclassified scientific works can be based on still secret data from government archives. In addition, the growing willingness of intelligence officials to collaborate with outside experts—inspired, in no small measure, by Medea—has had unexpected benefits. These are perhaps most evident in the field of emergency response, where highly classified satellite reconnaissance imagery has already proved invaluable to teams coping with the



STEVE JOHNSON AND LOU FANCHER

In a unique collaboration, scientists and intelligence officials are working together to find out what the U.S. government's vast secret archives can reveal about the earth



catastrophic volcanic eruption on the Caribbean island of Montserrat and with forest fires in Alaska.

Eyes in the Sky

The fact that most of the intelligence data are still not available to the general public makes it difficult to assess conclusively their applicability and utility to current topics in environmental science. Over the years, though, a fair number of details have been officially released, or have leaked out, regarding the characteristics and capabilities of the secret platforms and sensors that collected the data and the periods during which they operated.

The various photoreconnaissance satellites sent into orbit over the past 37 years, each of which pushed the limits of aerospace and optical technologies in its day, are among the best known of the intelligence technologies deployed in connection with the cold war. The most recent of these satellites are the Keyhole-11 (KH-11) and Advanced KH-11 satellites, which can return their imagery virtually instantaneously via a relay satellite. Nine KH-11 satellites were orbited between 1976 and 1988, and three Advanced KH-11 satellites have been launched in the 1990s. Those three Advanced KH-11s, each of which cost about \$1.5 billion, are still operating and returning images with a resolution of 15 centimeters (six inches) or better.

The U.S. government has yet to declassify data about the high-resolution satellite systems that operated from 1963 to 1984 (known as KH-7 and KH-8), the KH-9 wide-area-imaging reconnaissance satellite, or the KH-11 and Advanced KH-11. Nevertheless, a great deal of information has leaked out to the trade press, including examples of the imagery from these satellites. More information about the satellites was re-

leased in connection with the trials of former Central Intelligence Agency employee William Kampiles and naval intelligence analyst Samuel Loring Morrison, both of whom were convicted of making unauthorized disclosures concerning the KH-11.

The previous generations of Keyhole satellites, the KH-1 through KH-9 (the KH-10 program was canceled before a satellite ever flew), returned canisters filled with film of targets in the Soviet Union, China, Cuba, the Middle East and elsewhere. The KH-1 through KH-9 programs encompassed 144 satellite launches between 1960 and 1972, although not all the launches were successful. The satellites produced over 800,000 images, which were recently declassified [see "The Art and Science of Photoreconnaissance," by Dino A. Brugioni; *SCIENTIFIC AMERICAN*, March 1996]. This declassification, incidentally, was brought about partly because of the advocacy of Medea scientists. The cameras on the KH-1 satellites permitted resolution of objects about 12 meters (40 feet) apart; that resolution was improved to about 1.5 meters for the KH-4s.

The more advanced, higher-resolution KH-7, KH-8 and KH-9 contributed several million images in the 1970s and early 1980s. The unique KH-9 was capable of imaging tens of thousands of square kilometers in a single frame with a resolution of about two thirds of a meter. The KH-8 and KH-9 programs concluded in 1984.

With its infrared sensors, another group of satellites with apparent scientific utility is the U.S. Air Force's Defense Support Program (DSP) satellites, the first of which was launched in 1970 and the 18th in February 1997. Operating in geosynchronous orbits 35,900 kilometers above the earth, the main sensors on board the DSPs are infrared

MEETING OF TWO WORLDS—science and intelligence—poses problems in information dissemination but could have big payoffs for studies of the earth.

Selected Intelligence Systems and Their Scientific Uses

	PLATFORM NAME	YEARS OPERATED	SENSORS/SPECIAL FEATURES	MILITARY USES	SCIENTIFIC USES
SATELLITES	KH-1 – KH-6 KH-7 and KH-8	1960–1972 1963–1984	Recorded images on photographic film	Reconnaissance	Studies of the growth, shrinkage or integrity of arable land and forest, desert and other ecosystems; monitoring of coastline erosion, forest fires and volcanic activity
	KH-9	1971–1984	Wide-angle optics imaged thousands of square kilometers		
	KH-11 Advanced KH-11	1976–1995 1992 to present	Beamed images back to the earth in real time		
	DSP	1970 to present	Infrared	Detects missile launches, explosions and fires	Monitoring entry of meteors into the earth's atmosphere
	Lacrosse	1988 to present	Produces radar images in any weather at any time	Reconnaissance	Monitoring of ice and snow; location and trends in levels of remote lakes, streams and springlines
AIRCRAFT	U-2	1956 to present	Now records images electro-optically in real time	Reconnaissance	Studies of the growth, shrinkage or integrity of arable land and forest, desert and other ecosystems; monitoring of erosion and natural disasters
	SR-71	1964–1990	Could photograph over 260,000 square kilometers in one hour		
SHIPS	Survey ships (TAGS-60 series is newest generation)	1950 to present	Multibeam contour-mapping system; wide-beam deep-water system; subbottom profiler	Data on marine gravitational and magnetic fields; seafloor bathymetry and sediment properties; vertical profiles of salinity and temperature	Baseline data for future marine studies; calibration of satellite algorithms; more efficient salinity and temperature sampling
SONAR ARRAYS	SOSUS	Mid-1950s to present	Hydrophones	Identifying and tracking hostile submarines	Monitoring of ocean temperature; tracking population and movement of whales

BRYAN CHRISTIE

ones designed to detect the missile plumes of Soviet/Russian or Chinese intercontinental and submarine-launched ballistic missiles. The satellites also carry a variety of special-purpose sensors to detect the signatures from atmospheric nuclear explosions. Over the years DSP infrared sensors have also detected launches of intermediate-range missiles (including SCUDs), aircraft flying on afterburner, spacecraft in low-earth orbit and even terrestrial events such as large-scale explosions.

Another contributor to the vast imagery archive is a satellite program designated as Lacrosse. Its satellites do not photograph objects but rather transmit radio waves. Sensors on the satellite receive reflections of these waves, which can then be converted into an image of the target. Because radio waves penetrate cloud cover and are unaffected by darkness, Lacrosse gives the U.S. an essentially continuous imaging capability.

Except for the DSPs, which are operated by the U.S. Air Force, all the satellites just described were designed and operated under the auspices of the Na-

tional Reconnaissance Office (NRO), a formerly covert organization established on September 6, 1961, to coordinate the space reconnaissance efforts of the CIA and the air force. The office was once so secret that its name or acronym could be mentioned only in documents handled through a security system above the "Top Secret" level. Not until 1992 did the Department of Defense publicly acknowledge the existence of the NRO.

Not only satellites but also aircraft were used to produce the many photo-reconnaissance images in the archives. The best-known U.S. reconnaissance aircraft is the U-2, whose espionage role was dramatically revealed in the wake of the 1960 downing of CIA pilot Francis Gary Powers over the Soviet Union. The incident ended overflights of the Soviet Union, but for more than 40 years U-2s have been flying over and photographing targets across the globe. They are currently used to monitor Iraq's compliance with the terms of the 1991 cease-fire in the Persian Gulf War. Another reconnaissance aircraft, the air force's SR-71, operated from the late

1960s until its temporary retirement in 1990. (Two aircraft were returned to operational status recently but now appear headed back into retirement.) Flying at over 26,000 meters, at speeds greater than Mach 3, the SR-71s could photograph more than 260,000 square kilometers in a single hour. As a result, SR-71 missions produced photographs covering millions of square kilometers.

Ears in the Sea

Throughout the cold war, while the CIA, the NRO and the air force were busy photographing the territory of enemies and allies, the navy was operating a worldwide network of sonar arrays to keep track of the whereabouts and movements of Soviet submarines. The information was vital to the cat-and-mouse game being played by opposing submarines, in which ballistic-missile submarines strove to elude the attack submarines that would try to destroy them immediately in a nuclear war.

The sonar arrays are known as the Sound Surveillance System, or SOSUS.

During much of the cold war, about 20 SOSUS hydrophone arrays were deployed at various locations on the ocean floor to detect the acoustic signals generated by Soviet submarines. The arrays are sensitive enough to let experts identify not only classes but specific submarines. In addition, SOSUS can monitor the movements of naval ships on the surface of the ocean and even aircraft flying low over it.

Development work began on SOSUS in 1950 and led to the installation four years later of the first array of hydrophones on the continental shelf off the eastern coast of the U.S. The arrays have been periodically updated, and the technology is now in its fifth or sixth generation of development.

The data collected about each submarine include its sonar echo and the noises made by its engine, cooling system and the movement of its propellers. The sounds are translated into a single recognition signal that enables experts to determine not only the type—an Alfa-class attack submarine, say, or a Typhoon-class ballistic-missile submarine—but also the individual submarine.

Behind the Black Door

Although this global collection of sensors in sea, air and space ably performs the intelligence and military roles it was meant for, it remained to be seen whether its data, past and present, could benefit science. The largely bureaucratic process of answering this question began in May 1990, when then Senator Al Gore of Tennessee wrote to an official at the CIA. Gore wanted to know whether the agency possessed databases on the oceans, clouds, tropical winds and rainfall that would be relevant to various environmental and scientific issues. It turned out that the agency did have substantial data on many of the topics listed in the letter. Not long after, CIA officials arranged a meeting with a few scientists from outside the intelligence community, including Jeffrey Dozier, dean of environmental sciences at the University of California at Santa Barbara, and Gordon J. MacDonald, a geophysicist at the University of California at San Diego.

Prompted in part by another letter from Gore, Robert Gates, then director of the CIA, granted security clearances in the spring of 1992 to a group of scientists. The clearances enabled the scientists to study intelligence data with

an eye toward determining its scientific relevance. Eleven panels based on environmental disciplines were established; to staff the panels, about 70 scientists were recruited from academia, the private sector and government agencies such as the Environmental Protection Agency and the National Oceanic and Atmospheric Administration. At the first official meeting, in October 1992, the scientists considered environmental data needs and possible sources.

The scientists also met with some of their noncleared colleagues to compile a list of critical issues and the information that would be needed to address them. For example, one of the study groups, on greenhouse gases, identified ozone as a major concern. To better correlate the abundance of the molecule with climatic observations, the scientists agreed that they would need to know the vertical distribution of ozone as a function of season and latitude, with sufficient accuracy to detect a 5 percent change in 10 years.

Once the scientists had identified their information needs, the intelligence community—particularly the CIA and the NRO—and also the Defense and Energy departments began to prepare briefings on more than 100 classified systems and data sets. Then, in late November 1992 and early 1993, the scientists were ushered into the “black” world of U.S. intelligence technology and its products. The briefings on past and present collection systems ranged from space to undersea systems and included a multitude of details, such as their code names—a highly classified item of data for intelligence satellites—where they were located and the type of data they collected. Besides helping the scientists determine what archived data might be of value for environmental research, the briefings were designed to let them consider how currently operating satellites, sonar arrays and other systems could be employed to collect environmental data.

In December 1993 the scientists concluded in their first report that there were in fact wide-ranging environmental-scientific uses for the vast archive of imagery data and for current photoreconnaissance satellites. One obvious use of the archived images, they noted, would be the filling in of gaps in data about changes in patterns of urbanization as well as in boundaries of vegetated regions and deserts—changes that are understood to be sensitive indicators of climate change. The first civilian system,

the Earth Resources Technology Satellite, was not launched until 1972, and the classified imagery archives would permit an extension of the data timeline back to the early 1960s.

The scientists also realized that images from the spy satellites would permit “calibration” of the lower-resolution civilian systems. By comparing low- and high-resolution images of the same target, the scientists could extract additional information from the low-resolution photographs. This calibration would be especially helpful for vegetation data, allowing, for example, the determination of species and the degree of foliage coverage.

High-resolution images could also provide an additional level of detail that would be useful in studying the growth or shrinkage of forest, desert or wetlands. Moreover, the images could facilitate more detailed studies of changes in arable land, the integrity of ecosystems and animal habitats, forest damage from pollution or other human activity, water use and coastline erosion—all subjects with considerable consequences for human health.

The report also noted that the DSP satellites could be used to detect and monitor large fires in remote regions; such fires generate the greenhouse gases carbon monoxide and carbon dioxide. And it suggested that the SOSUS arrays could be used to detect global warming: sound travels faster through warm water than through cold water, so measurements of changes in sound speed over thousands of kilometers of ocean reveal even minute changes in temperature. SOSUS could also be used to monitor the movements of whales, yielding new information on their populations. All these suggestions have since led to active efforts under Defense Department or other auspices.

Approximately 15 experiments were also proposed to try to ascertain whether intelligence systems could be used to determine the thickness of sea ice, the extent of deforestation, tropospheric water content and the existence of radioactive, toxic waste below ground.

Medea Becomes Permanent

Encouraged by the success of the partnership, the intelligence community moved in 1994 to make it permanent. The name Medea, chosen by CIA official Linda Zall, came from the character in Greek mythology who



SOUND SURVEILLANCE SYSTEM, or SOSUS, consists of arrays of hydrophones deployed on the ocean floor. During the early 1980s, some 66 arrays were operating at the locations shown here; in the wake of the cold war, the number has been reduced.

helped Jason and the Argonauts steal the Golden Fleece and who later became Jason's wife. (Not coincidentally, Zall is the CIA's representative to a group of scientific advisers to the military that is known as Jason.) There are still approximately 70 scientists who have security clearances as well as access to a program office in McLean, Va., near CIA headquarters.

So far Medea scientists have produced well over a dozen reports on how archived data and present collection systems can advance environmental science. The reports cover such subjects as improving predictions of volcanic eruptions, better methods of identifying and delineating wetlands, improving estimates of surf conditions and ocean circulation, and calculating glacier net balance. All the reports except one are classified.

The single unclassified report, *Scientific Utility of Naval Environmental Data*, was published in June 1995 and resulted from a navy request to Medea to examine the databases, products and capabilities of the Naval Meteorology and Oceanography Command. One focus of the effort described in the elegant, 52-page report was the examination of the scientific utility of the oceanography command's databases on sea ice, geology and geophysics as well as ocean volume and boundary properties. It also includes a number of recommendations on enhancing ocean science capabilities. For example, it proposes the establishment of an exploitation center to allow cleared scientists access to most of the command's databases and suggests that

the navy step up its efforts to build regional ocean models, which simulate sea conditions on computers.

Medea scientists have also been asked to explore how modifications to current and planned satellite systems can improve their utility for collecting environmental data. The result has been approximately a dozen or so "fairly esoteric" dual-use reports to the NRO, in the words of one of its officials. The studies contain specific engineering recommendations and are, according to the same official, "taken seriously" and "will have an impact" on future intelligence satellites.

Medea has also been instrumental in the design of the Global Fiducials Program, under which approximately 500 sites of interest to environmental scientists will become repeated targets of present and future imagery satellites. Among the prospective targets are clouds off the California coast between Los Angeles and San Diego; a lowland tropical rain forest at La Selva, Costa Rica; the Luquillo experimental forest in Puerto Rico; permafrost in Fish Creek, Alaska; glaciers in Griegslætcher, Switzerland; and the high slopes of Mount Kilimanjaro in Tanzania.

Herman H. Shugart, a Medea member and environmental scientist at the University of Virginia, hopes that decades from now the images of Mount Kilimanjaro will provide evidence of any increase of carbon dioxide in the atmosphere. One of the first natural indicators of such a buildup would be a thickening of vegetation in the highest vegetation zones, such as those on Kili-

manjaro, found in high tropical forests. Such an increase in verdancy would be easily visible in reconnaissance images.

The images will be stored in a classified library at the U.S. Geological Survey. For the next couple of decades, the data will be available only to those with the proper clearances. But declassification is expected to make the vast database available eventually to academic scientists and graduate students.

Even so, the delay has drawn criticism. Steven Aftergood, director of the Project on Government Secrecy of the Federation of American Scientists, declares it "admirable that the intelligence community will be expanding the collection of environmental data." He hastens to add, however, that he finds it "troubling that they will maintain [the data] as classified for decades."

Science and Secrecy

Although most of the work of the Medea scientists has been devoted to the many reports about intelligence data and systems and their scientific utility, three scientific papers have been written so far based on classified data. The papers offer an intriguing initial look at the evolving, still somewhat uneasy balancing act between the concerns of security and those of science.

The twin pillars of science are replicability—the ability of one scientist to reproduce another's findings using the same data—and verifiability—the ability to demonstrate the validity of the findings through experimentation or observation. Peer reviewers also often want to know about how, and how well, the data were collected. Here the relevant questions are: What instruments were used? What capabilities did they possess? How often were measurements taken and under what conditions?

The use of classified data topples the first pillar, because noncleared scientists (that is, virtually all academic scientists) cannot gain access to the information. In addition, peer reviewers will be left at least partially in the dark when they inquire about the collection mechanisms and procedures.

Dozier notes that in some cases the results of such research can be verified, even if they cannot be replicated, which would increase confidence in the classified methods and data used to produce the results. For example, the accuracy of a topographic map of the seafloor can be checked, even if the means

by which it was originally produced are not known. At the same time, he acknowledges, such an approach “doesn’t work for transient phenomena”—ocean and atmospheric features could well be gone by the time other scientists seek to verify the results.

Many of these issues are on display in connection with the first two scientific articles to result from Medea. The one by Medea scientist William H. Schlesinger of Duke University and Nicholas Gramenopoulos of Mitre Corporation was published in 1996 in *Global Change Biology*. The article addressed the question of whether the desert in relatively pristine areas of the Sudan was on a southward march. Availing themselves of satellite and aircraft reconnaissance photographs of the western Sudan taken between 1943 and 1994, the authors analyzed the abundance of trees at about a dozen sites arrayed in a north-south direction. The photographs greatly extended the record of vegetation change in the African Sahel as produced by NOAA’s satellite-borne Advanced Very High Resolution Radiometer since 1980. The authors noted that the expansion of desert would imply that regional or global climate change was increasing the probability of famine; what they found, however, was no evidence of significant change.

The fact that many of the images the authors relied on in formulating their conclusions are in classified archives ensured that Schlesinger’s article did not appear in the journal *Science*, to which it had originally been submitted. Schlesinger recalls that the reviewers for *Science* asked questions about availability, resolution and frequency of coverage that he simply could not answer without divulging classified information. Although *Science* does not have a blanket policy prohibiting publication of such articles, its managing editor, Monica M. Bradford, comments that “if reviewers can’t judge what is presented, we’re not going to publish.”

Information about the sensors is almost entirely missing. The authors state that “we used the archive of remotely sensed photography from aircraft and satellites operated by the Intelligence Community and Department of Defense to provide a record of the abundance of woody vegetation in Darfur Province, western Sudan.”

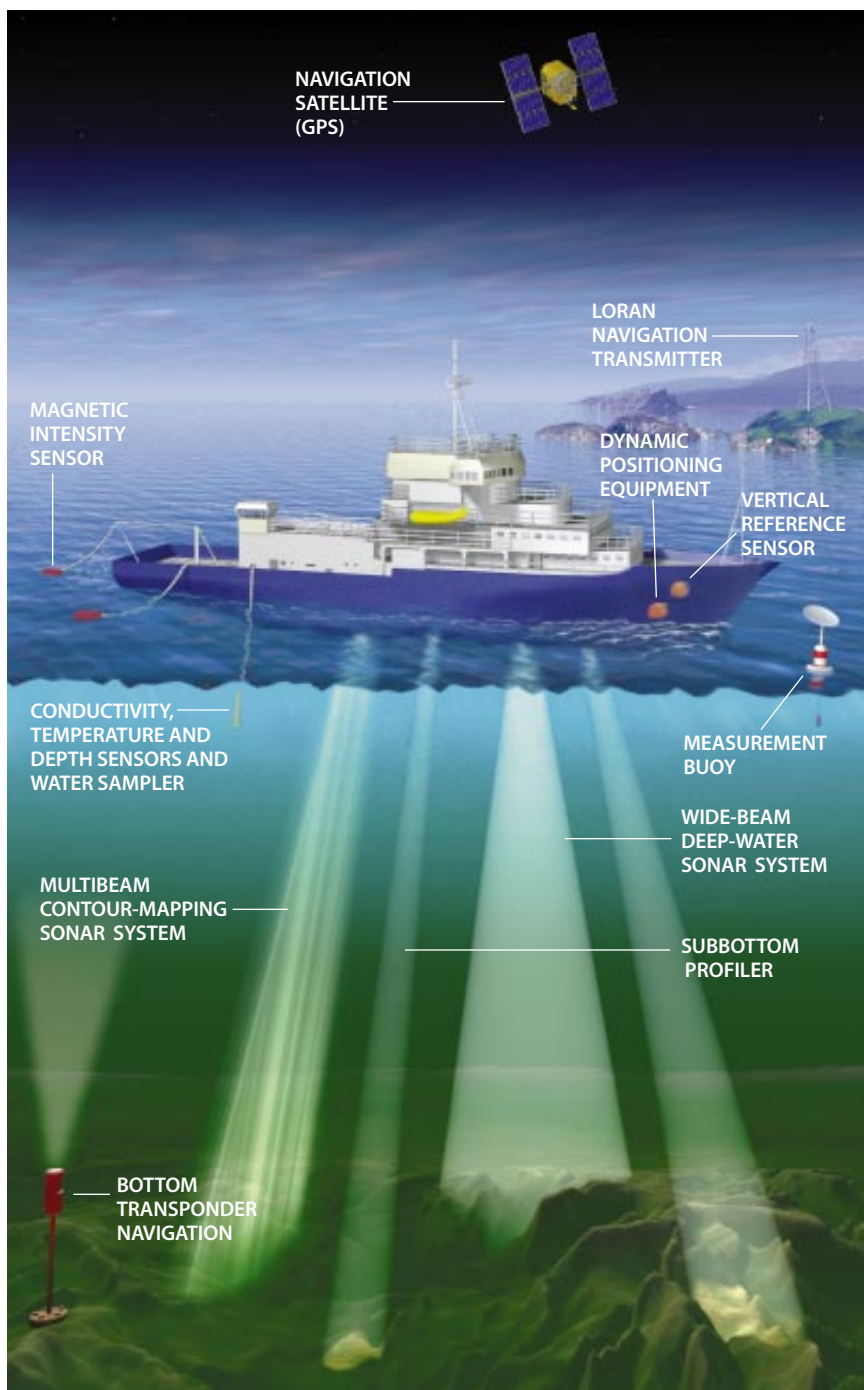
The editors of *Global Change Biology* felt it necessary to add to the article a caveat, which reads: “Many of the

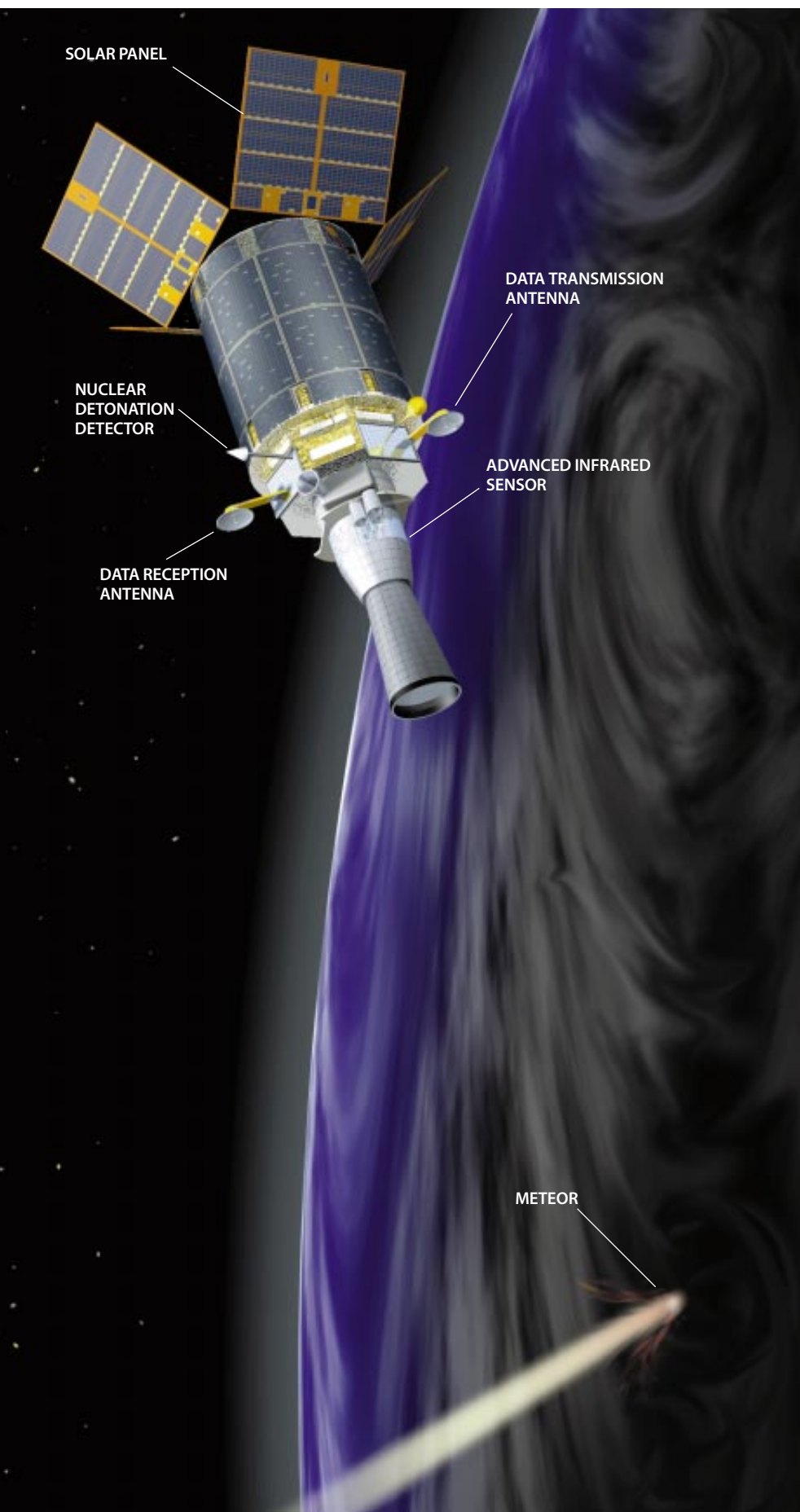
data for this paper are in classified intelligence archives. As a consequence, the options for evaluating the paper and for ensuring that other scientists can reproduce the analysis are constrained. Publication of this paper in *Global Change Biology* is intended to illustrate the potential use of, and stimulate discussion on the role of, classified data in

the open scientific literature. Limitations on access to the data make it impossible for the journal’s usual review process to assess all aspects of data quality, selection or interpretation.”

Another Medea-inspired article addresses a subject of growing interest among astronomers and the general public: the possibility of a sizable mete-

SURVEY SHIP, designated TAGS-60, is the latest in a series dating back at least four decades. The U.S. Navy ship, along with other military resources such as Global Positioning System (GPS) satellites and long-range (“Loran”) radio navigation, is equipped with a variety of sensors to measure militarily useful ocean parameters. Sonar systems map the seafloor and even probe the area just below the floor.





MILITARY SATELLITE known as DSP (for Defense Support Program) has infrared sensors capable of detecting the entry of sizable meteors into the earth's atmosphere. On February 1, 1994, a DSP recorded the arrival of a meteor that exploded on entry, releasing as much as 630 kilotons of energy. The satellites orbit geosynchronously at 35,900 kilometers.

oroid crashing into the earth. The article was co-authored by Medea member Thomas B. McCord of the Hawaii Institute of Geophysics and Planetology.

Interest in the meteoroid-impact issue had previously led the air force to declassify data from the first 17 years, starting in 1970, of the DSP program. The DSP satellites were designed to detect the infrared energy released by explosions ranging in intensity from the destruction of an airplane to a nuclear detonation. When a reasonably sizable meteoroid enters the earth's atmosphere, it, too, explodes, emitting a unique infrared signature that is detectable by the DSPs.

McCord's security clearance enabled him to pore over more recent DSP records and possibly other data as well concerning a meteoroid that slammed into the earth's atmosphere on February 1, 1994, over the central Pacific Ocean not far from the island of Kosrae. McCord estimated that the mass of the meteoroid was between 500,000 and nine million kilograms. Unconfirmed reports have held that the explosion of this meteoroid was so great that President Bill Clinton was awakened in the middle of the night by jittery officials fearing that a nuclear weapon had detonated in the atmosphere.

McCord's analysis of the event was published in the February 25, 1995, issue of the *Journal of Geophysical Research*. The records from the DSP and possibly other sensors enabled McCord to estimate the meteoroid's orbit, mass, fragmentation and energy release—which was calculated to be between 34 and 630 kilotons. The paper provided a detailed account of where the meteoroid was first detected (at an altitude of 54 kilometers), its tracking, its angle of entry, its breakup in the atmosphere and how the authors calculated its orbit and energy release.

They did acknowledge that “we must be vague concerning sensor characteristics that we are not yet at liberty to reveal” and made no explicit reference to the DSP. The extent of the disclosure

DAVID FIERSTEIN

about the sources of their data was the revelation that the sensors included “infrared and visible wavelength sensors aboard platforms operated by the U.S. Department of Defense.”

Emergency Intelligence

It is not part of their official mandate, but Medea members have also been assisting the intelligence community in its work in monitoring environmental degradation and emergency situations. The environmental tasks, especially, were assigned greater priority in 1993 when Presidential Review Directive-12 announced that President Clinton had decided that “environmental issues are significant factors in U.S. national security policy.”

In their environmental activities, some of which are focused on Russia and eastern Europe, Medea scientists have assisted intelligence community analysts in assessing the effect of a series of oil spills in the Komi region of Russia and of Russia’s disposal of chemical weapons in the Arctic. According to an NRO official, the imagery analysts at the Defense Department’s National Imagery and Mapping Agency “learned some tricks” from the scientists with respect to processing and also “fusing” data—combining the output of different sensors (such as visible-light and radar imagers) and using it to produce a single product (such as an image) that contains more information than any of its components.

Several Medea scientists have also been participants in the Environmental Working Group of the commission headed by Vice President Gore and Russian Premier Viktor Chernomyrdin. Among the group’s efforts has been the exchange of satellite imagery and imagery-derived data to assist in the environmental cleanup of areas surrounding military facilities.

Recent emergencies that have attract-

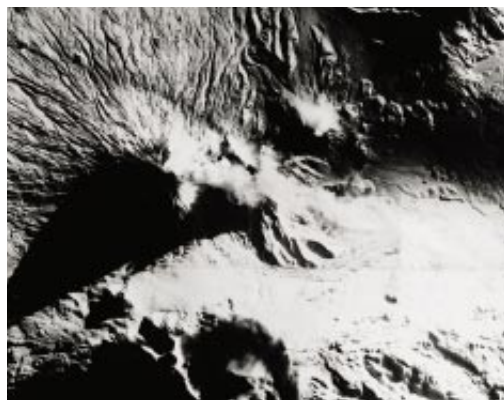
ed the attention of the intelligence community and Medea include the flooding in the winter of 1996–97 in northern California and subsequent hurricane damage in the southeastern U.S. Medea researchers also helped to monitor changes in the volcano on Montserrat shortly before it erupted in 1995. The monitoring led to an official warning to the island’s government, which was able to evacuate 4,000 people from the danger zone.

Tracking the wildfires that raged in Alaska in June 1996 presented a problem for the U.S. Forest Service, which did not have enough airplanes to chart the extent of the fire. The task was an easy one, however, for reconnaissance and the DSP satellites.

Medea’s Future

Although Medea has had undeniable successes, a few issues will need consideration in the near future, especially if the program expands. Among them is a fear that extensive use of classified data by civilian agencies could inhibit free and open discussion of some of their policies. The worry is that officials will be restricted in their public remarks and, moreover, that outside experts will lack full access to the data on which policies are made and justified. Another concern is that use of intelligence systems for environmental research will inhibit the use of a planned generation of relatively high resolution commercial satellites for environmental research—the results of which could be made available immediately to a much wider audience.

Already one misgiving—that nonintelligence applications would take up too much of the time of key intelligence resources—has been proved unfounded.



U.S. DEPARTMENT OF DEFENSE

VOLCANO, one of the world’s highest, is on the Kamchatka Peninsula in Russia’s far east. Comparison of reconnaissance images, such as this one from 1962, provides insights into the history of volcanic activity on the peninsula, an extremely active area both seismically and volcanically.

According to Bo Tumas, the CIA’s environmental intelligence program manager, the environmental collection effort occupies less than 1 percent of the time of reconnaissance satellites.

Against these worries must be weighed the demonstrated and potential benefits of Medea. In addition to promising the availability of a well-designed environmental database for scientists in the 21st century, Medea serves as a well-informed advocacy group in favor of further declassification. For example, Medea scientists have already proposed releasing environmentally relevant satellite imagery up through the present, with the true resolution of present satellites obscured by the release of coarser images. Intelligence officials ultimately rejected the proposal, but without the Medea program, such a possibility probably would not have even been considered.

Clearly, Medea itself is as much an experiment as is the work of its participants. And as with any experiment, there will be theories, unexpected findings and, one hopes, progress as this unique collaboration between scientists and spies matures.

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The Author

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The Viking Longship

Long, narrow ships packed with warriors helped to make the Vikings the dominant power in Europe for three centuries, beginning in about A.D. 800

by John R. Hale

In September 1997 Danish archaeologists discovered a Viking longship in the mud of Roskilde harbor, 40 kilometers (25 miles) west of Copenhagen. The discovery was the kind of serendipitous event that earned Viking Leif Eriksson the appellation "Leif the Lucky." Lying unsuspected next to the world-renowned Viking Ship Museum at Roskilde, the longship came to light during dredging operations to expand the harbor for the museum's fleet of historic ship replicas.

According to Ole Crumlin-Pedersen, former head of the museum, the longship must have been sunk by a storm

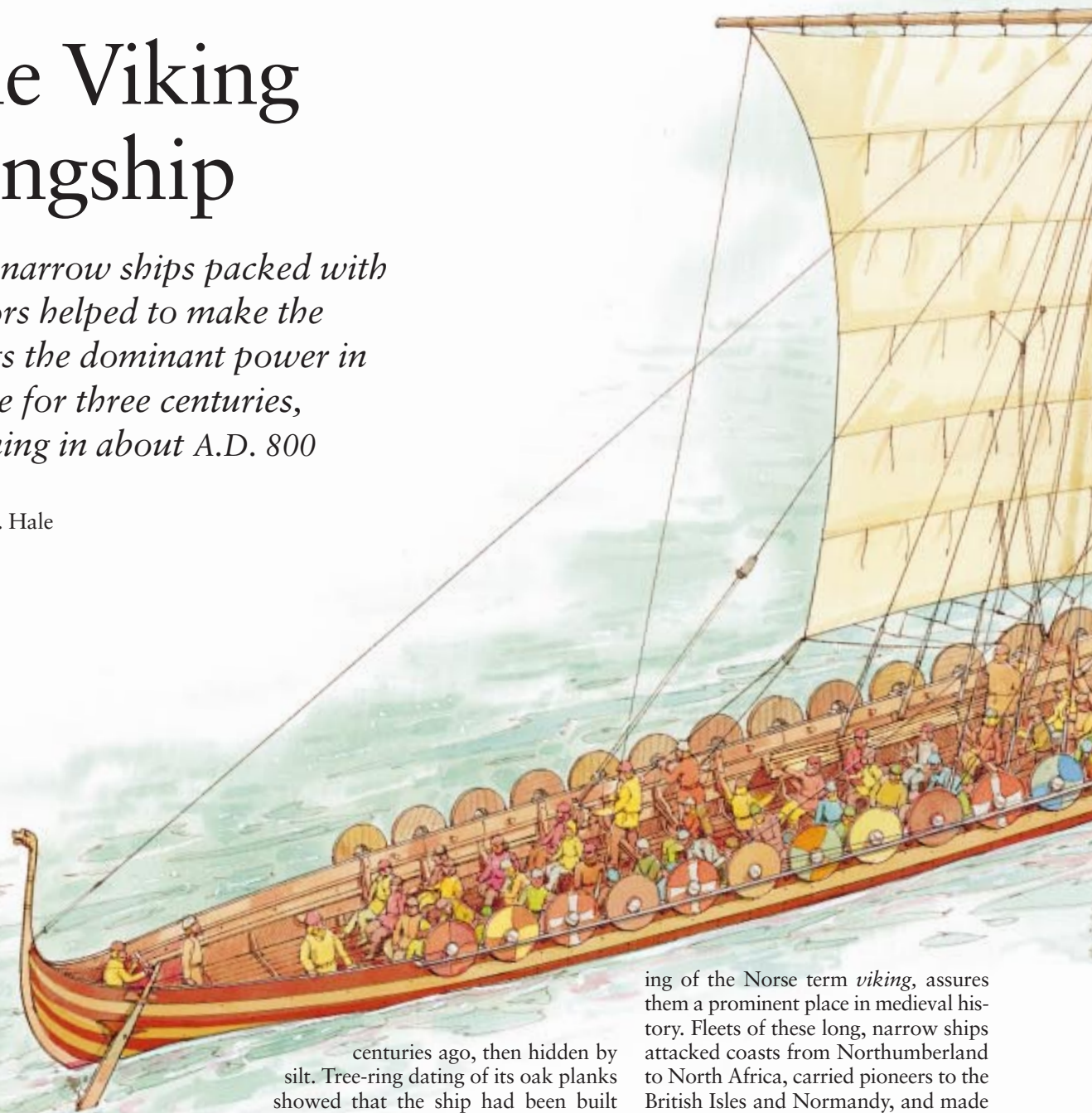
centuries ago, then hidden by silt. Tree-ring dating of its oak planks showed that the ship had been built about A.D. 1025 during the reign of King Canute the Great, who united Denmark, Norway, southern Sweden and England in a Viking empire.

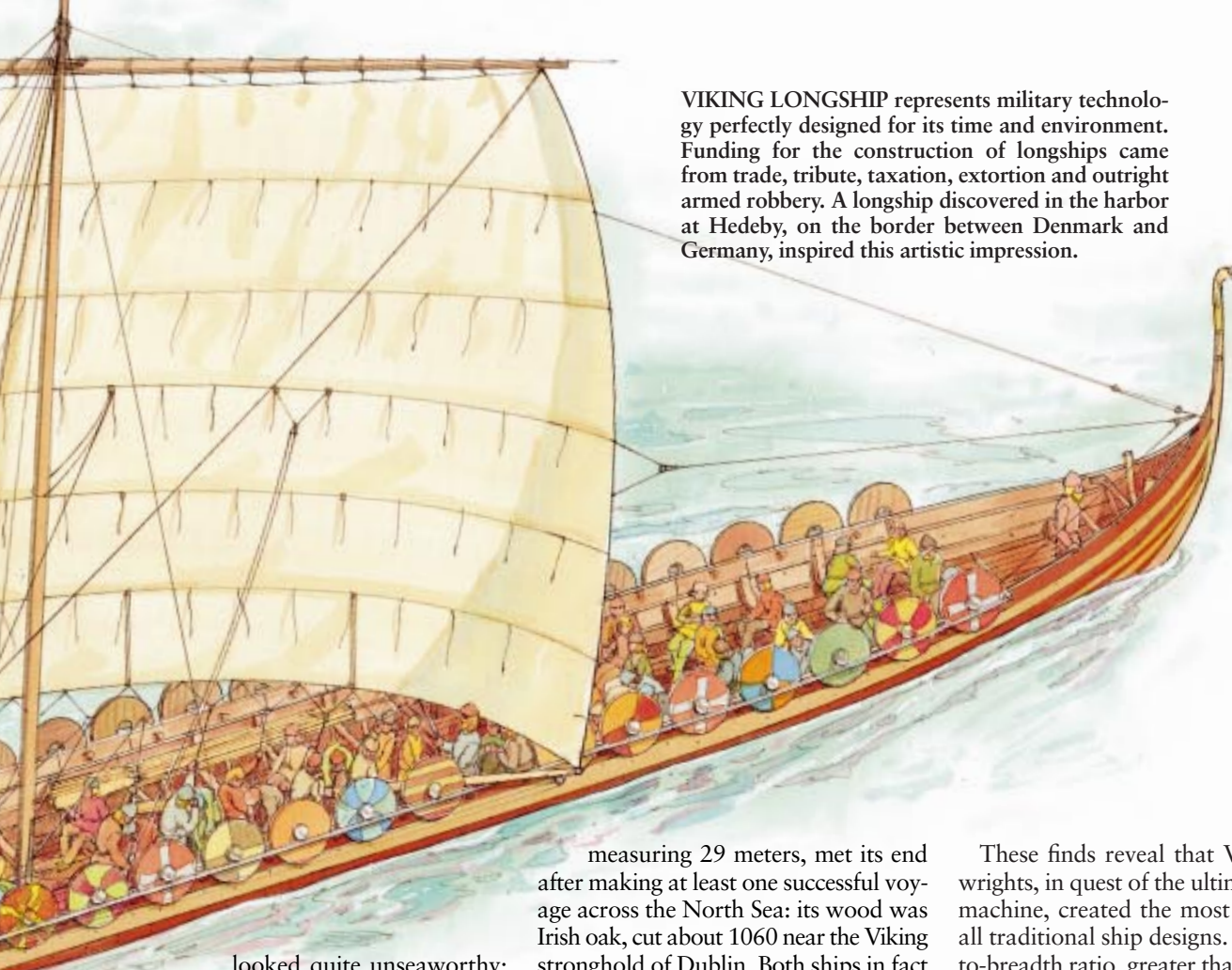
With its immense length of 35 meters, the Roskilde longship surpasses all previous longship finds. By doing so, the ship also refuted skeptical modern scholars who judged these leviathans, described in Norse sagas, to be as mythical as the dragon whose name they bore. (Longships became known generally as dragons.) The sagas had been accurate in their accounts of "great ships," the largest class of Viking warship.

The passage of a millennium has not dimmed the pride Scandinavians feel for the Viking longships. Their vital role in seaborne raiding, which is the mean-

ing of the Norse term *viking*, assures them a prominent place in medieval history. Fleets of these long, narrow ships attacked coasts from Northumberland to North Africa, carried pioneers to the British Isles and Normandy, and made the Vikings the dominant sea power in Europe from about A.D. 800 to 1100, the Viking Age.

Although finds of various Viking ships and boats have been made since 1751—most spectacularly in the royal burial mounds at Gokstad and Oseberg in Norway—the classic longship itself proved elusive until 1935, when Danish archaeologists excavated a chieftain's burial mound at Ladby. Only the shadow of a ship remained, with dark-stained soil revealing the form of the hull. Iron spirals marked the crest of the dragon's head at the prow, and seven long rows of iron rivets on either side still followed the lines of the vanished planks. The Ladby ship was much narrower than the celebrated Norwegian ships and





VIKING LONGSHIP represents military technology perfectly designed for its time and environment. Funding for the construction of longships came from trade, tribute, taxation, extortion and outright armed robbery. A longship discovered in the harbor at Hedeby, on the border between Denmark and Germany, inspired this artistic impression.

BARRY ROSS, AFTER SUNE VILLUM-NIELSEN

looked quite unseaworthy: 20.6 meters long, only 3.2 wide amidships and a mere meter from the keel to the top plank. Critics dismissed as implausible the accounts in the sagas of much larger longships with the same extreme proportions.

Actual timbers of a longship were located in 1953 in Hedeby harbor, site of a prosperous Viking emporium on the German border. Although the ship was not raised, public interest ran so high that the diver who discovered it made a radio broadcast underwater; his fascinated audience included 18-year-old Ole Crumlin-Pederson. By age 22, he had embarked on a series of finds that exploded the timid theories of the skeptics and ultimately involved him in the retrieval and study of every longship discovered since Ladby.

Peaceful burial mounds had yielded prior finds, but Crumlin-Pedersen specialized in disaster sites. Between 1957 and 1962 he was co-director of the team that recovered two longships and three other Viking ships from a blockade in a channel near Skuldelev, where desperate Danish townsfolk in the 11th century had deliberately sunk the ships to create a barricade against invaders. The bigger of the two Skuldelev longships,

measuring 29 meters, met its end after making at least one successful voyage across the North Sea: its wood was Irish oak, cut about 1060 near the Viking stronghold of Dublin. Both ships in fact showed many seasons of wear, evidence that longships were more seaworthy than some scholars had thought.

In 1979 Crumlin-Pedersen fulfilled a dream of his youth by leading the excavation of the Hedeby longship. It proved to have perished as a fire ship, a vessel intentionally set ablaze as an offensive weapon, during an attack on the town in about 1000. Here, too, the wood was remarkable: local oak cut from 300-year-old trees in lengths exceeding 10 meters without a knot or blemish.

An Evolved Design

The five longships discovered since 1935 show the full range of the species. Small levy vessels of up to 20 rowing benches (Ladby and the little Skuldelev warship) were maintained by local communities for royal service, to answer the call whenever the king sent around the symbolic war arrow. Standard longships of up to 30 rowing benches (Hedeby and the big Skuldelev warship) were the pride of Viking earls and kings, displaying craftsmanship of superb quality. The "great ships" of more than 30 rowing benches (Roskilde) appear only in the dynastic wars of the late Viking Age.

These finds reveal that Viking shipwrights, in quest of the ultimate raiding machine, created the most extreme of all traditional ship designs. The length-to-breadth ratio, greater than 6:1 and a rapierlike 11.4:1 in the Hedeby longship, combined with the shallow draft to allow longships to land on any beach and penetrate virtually any waterway in Europe. With speed as a goal, whether under oars or sail, expert shipwrights achieved strength through resilience and lightness. They pared the planking to a thickness of two centimeters—a finger's breadth—and trimmed every sliver of excess wood from the rib frames. Yet this drive for technical perfection produced a masterpiece of beauty as well, above all in the noble curves of stem and stern. A court bard sang the praises of King Harald Hardruler's dragon: "As Norsemen row the serpent, the riveted [ship], down the icy stream, it is like a sight of eagle's wings." Plato may have denied the existence of ideal forms in this world, but Plato never saw a Viking ship.

The longship's perfect mating of design, structure and material derives neither from a single creative genius nor even a single age. Rather these vessels represent the culmination of 6,000 years of technical evolution.

The primeval ancestors appear to be Stone Age dugout canoes, the earliest dating to about 5000 B.C., which have been found at many coastal sites in

Denmark. Using flint tools, boatwrights sculpted logs of soft, durable linden wood to an even thickness of two centimeters. As in all dugouts, the shell itself provided structural integrity, a true exoskeleton. The canoes reached lengths of 10 meters and seem to have been paddled out to sea for cod fishing, whaling and raiding expeditions. Some canoes later served as coffins. The creators of dugouts bequeathed to their successors the ideal of light, open vessels with shallow draft and a long, narrow hull.

About 3000 B.C., boatbuilders along the Åmose River in Denmark began to bore a row of holes along the upper edges of their dugout canoes. They could then secure the lower edge of a plank, with matching holes, to the top of the dugout with cords of sinew or fiber. The resulting overlap marked the birth of

the distinctive northern European construction technique known as lapstrake, a strake being a line of planking. The added plank improved seaworthiness by increasing the extended dugout's "free-board," the distance between the waterline and the hull's top. Axes of Danish flint found far to the north in Norway and Sweden bear witness to the adventures of these Stone Age voyagers.

During the Bronze Age (2000 to 500 B.C.), the watercraft of Scandinavia took on some of the appearance of the future Viking ship, including high posts at each end crowned with spirals or animal heads. Some of these heads are certainly serpents or dragons, and dragons are depicted hovering over boats in Bronze Age art. The warriors manning these boats often wore the horned helmets that have come to symbolize the

caricature Viking of opera or cartoons. In fact, such headgear was quite out of fashion by the true Viking Age.

The designs on Bronze Age metalwork and rock carvings show boats with a beak at the prow. Although unfamiliar in European watercraft, the same structure could be found in the early 20th century on extended dugouts with sewn plank sides in Siberia, central Africa and the South Pacific. The beak was in fact the projecting tip of the dugout underbody. With a curved branch attached, it acted as a cutwater to protect the vulnerable stem where the planking closed off the forepart of the hull. Eventually, the wooden cutwater of the Bronze Age Scandinavian design would coalesce with the ornamented end post to form the great curved prow of the Viking ship.

The beak became the prominent fea-

LONGSHIP COMBINED THE FUNCTIONS of oceangoing troop carriers and amphibious landing craft. Its remarkably shallow draft enabled a longship to approach almost any beach or to invade deep inland via a waterway only a few meters deep. The more than 60 warriors on the largest ships could jump over the low side of the hull within a few strides of land. A medieval prayer captured the terror: "From the fury of the Norsemen, good Lord deliver us."



The Realm of the Longship

Major routes of Viking longship expeditions. All coastal settlements were open to attack.



BARRY ROSS



LONGSHIP FINDS appear on map as red dots. Boats ancestral to longships were found at sites marked with blue dots.

Longship Ancestors



Dugout canoe from Lystrup, Denmark, circa 5000 B.C.



Extended dugout canoe from Åmose, Denmark, circa 2500 B.C.



Beaked war canoe from Østfold, Norway, circa 1000–500 B.C.



Double-beaked war canoe from Hjørtspring, Denmark, circa 350 B.C.



Expanded dugout canoe from Bornholm, Denmark, circa A.D. 1–200



Oared warship from Nydam, Denmark, circa A.D. 300



Oared warship with keel and fixed side rudder from Kvalsund, Norway, circa A.D. 700

ture of war canoes at the beginning of the Iron Age (500 B.C. to A.D. 400), a time of severe climatic and economic stress in northern Europe. Too high and too flimsy to serve as a ram, the beak must have been preserved by boat-builders because it protected and stabilized the hull. Shipwrights deemed the beak valuable enough to include it at both ends, creating, in the Iron Age, the first truly double-ended design.

A bog near Hjørtspring, Denmark, yielded an early Iron Age canoe—complete with paddles, weapons and other gear—built in about 350 B.C. With its symmetric beaks and large steering paddles at each end, the Hjørtspring boat could have reversed directions without turning. Such adaptability might mean

the difference between life and death when encountering enemies in a narrow fjord or pushing off after a raid on a hostile shore. For the next 1,500 years, all Scandinavian warships would maintain the double-ended design of the Hjørtspring boat, even after the fixing of rudder, mast and sails had irrevocably distinguished the bow from the stern. The trait was unique: even the Romans, who left little commentary on Scandinavia, felt compelled to mention the double-ended boats.

Some Stone Age features still survived in the Hjørtspring boat, such as the use of linden for the hull and the stitching of the lapstrake planks with fiber cords. But the dugout underbody almost disappeared, trimmed down to a narrow

bottom plank bent in a gentle curve—a step toward the Viking keel. The elevated ends kept the vessel drier as it breast-ed oncoming waves, whereas the deeper midsection improved handling during turns. (Future shipwrights inherited this curve. Viking ships had keels 30 centimeters deeper amidships than at the ends, a refinement almost as subtle as the entasis of the Parthenon's columns but adopted for function rather than appearance.)

The 20 warriors who paddled the Hjørtspring canoe sat in pairs on intricate frames of linden, ash and hazel. The 90-centimeter interval between frames allowed each paddler ample room. As this spacing became standardized, Scandinavians began to compute the length

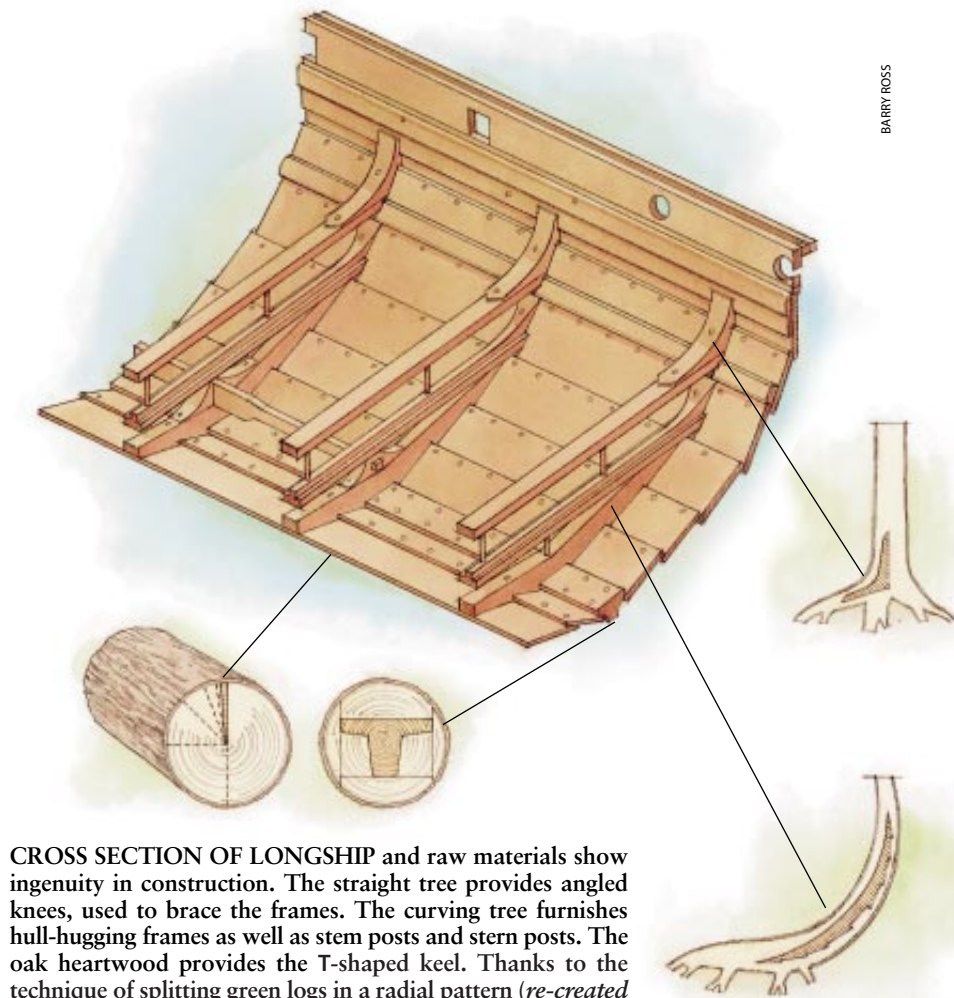
of a vessel by counting the “rooms” between its frames or benches. Coupled with the narrow bottom plank, the widely spaced frames allowed the hull remarkable flexibility; as in the ancestral dugout, the shell, rather than any rib structures, conferred strength. The lithe hull enabled the Hjortspring canoe, like later Viking ships, to snake its way through the water like a living creature.

Innovations in Design

In the later Iron Age, thanks to an act of technological crossbreeding, the complicated end structures of the Hjortspring canoe dropped out of the evolutionary line in favor of a far more elegant and simple solution to the problem of closing off the end of a hull. According to Crumlin-Pedersen, the innovation came from the expanded dugout canoe, a type that appears for the first time in Iron Age graves on the Danish island of Bornholm. Worldwide, makers of dugout canoes at times have been confronted with tree trunks too slender for a simple dugout. Independently, they worked out techniques for making a tubelike hollow in the log with an open slit on top, hewing the wood as thin as possible and then gradually expanding the sides by applying heat and inserting longer and longer stretchers. As the sides flared outward, the ends would draw upward into symmetric, curved points: the inspiration for the graceful design of the future Viking ship.

A vessel found at Nydam, north of Hedeby, is the earliest surviving offspring of the cross between the design of the expanded dugout and the lapstrake construction of the Hjortspring canoe. The late Iron Age Nydam vessel, built about A.D. 300, marks a fresh start on many counts. The planks, ribs and end posts were oak; clenched iron nails supplanted the stitches of earlier times; and the crew sat backward and propelled the vessel with long oars looped to rowlocks on the top strake. Most important, the five broad strakes on each side extended all the way to the low curving stem posts and stern posts, thus establishing the classic Viking prow structure.

An even more revolutionary change appeared about 700, just a century before the first important Viking raids. A ship from Kvalsund in western Norway sported an embryonic keel; the ever narrowing bottom plank finally acquired verticality with a T-shaped cross section. A fixed side rudder, the descendant of



CROSS SECTION OF LONGSHIP and raw materials show ingenuity in construction. The straight tree provides angled knees, used to brace the frames. The curving tree furnishes hull-hugging frames as well as stem posts and stern posts. The oak heartwood provides the T-shaped keel. Thanks to the technique of splitting green logs in a radial pattern (*re-created by neo-Vikings, below right*), all hull planking had the same cross section, which guaranteed uniformity of strength and resilience throughout the ship.

the steering paddle held over the side of earlier canoes, further stabilized the ship by projecting below the hull to prevent side slipping, like a modern centerboard. Thinner strakes, now eight in number, would make possible the more complex curves of the longships. The hardy Scandinavians stoically accepted the extra leaking around all these new seams. A Norse law regarded a boat unseaworthy if it needed bailing thrice in two days. (The crew could still choose to assume the risk.)

The Kvalsund ship's keel and side rudder heralded the arrival of leading performers in the drama of ship evolution that remained mysteriously in the wings until the dawn of the Viking Age: the mast and sail. Gravestone art on the Swedish island of Gotland began to depict ships with sails by 700, although the earliest physical remains of a mast come from a royal ship built in about 815 and buried at Oseberg in about 835. By then, the sail had been evolving for over four millennia, and Celtic sailing ships had





VIKING SHIP MUSEUM, ROSKILDE

LONGEST VIKING LONGSHIP was uncovered in 1997. The discovery site just outside Roskilde's Viking Ship Museum could not have been more convenient for the team of scientists, led by Morten Gøthche. Team members, two of whom are shown here, work from scaffolds suspended above the waterlogged oak timbers.

did, and want to be blown across the sea." In the long run, however, the advantages offered by the sail prevailed.

A pole, or spar, on the deck connected to a lower corner of the sail. Moving the spar angled the sail, which allowed the ship to tack into the wind. Rowing had carried the immediate ancestors of the Vikings east to Russia and west as far as the British Isles, but with the sail, the explosive career of the Vikings truly started. And the sail dictated most of the final steps of Viking ship evolution, including deeper keels, broader hulls and higher sides. The Viking longships, the direct descendants of the Stone Age canoes, soon found themselves surrounded by a family of related ship types that took advantage of the evolutionary potential to be found in the mast and sail. New designs proliferated, like Darwin's finches in the Galápagos, to fill every available environmental niche. Many

been plying the seas near Scandinavia since the time of Caesar. Norwegian archaeologist Arne Emil Christensen, the greatest authority on early Viking ships and the introduction of the sail, speculates that resistance to sailing may have been less technical than cultural: tough men row. Elder Vikings at the time "must have scorned the young," Christensen writes. He imagines them deriding their sons, "who were too lazy to row as we

of the newcomers were specialized sailing ships built for trade, exploration and colonization, such as the famous knorrs—stout ships with deep holds that carried Vikings across the Atlantic to America. As funeral vessels, these various ships and boats transported pagan Vikings on their final voyage; where ships could not go, in this world or the next, Vikings did not venture.

Small boats of Viking design would persist for centuries as cargo craft or church boats in such remote regions as the isles of western Norway or the Swedish lakes. But after 1100, the humble, flat-bottomed Hanseatic cog became the forebear of the next great line of sailing ships, including even the flagships of Scandinavian monarchs. The Viking longship, designed for raiding, could not compete in a world of fortified port cities, organized naval warfare and kings who demanded the pomp and comfort of a cabin when on board. The last naval levy of Viking warships was called out in 1429 and defeated by seven cogs. The dragon had retreated into the realm of legend.

Replicating the Design

From Captain Magnus Andersen's *Viking* of 1893 (a replica of the Gokstad ship from Norway), a long line of reconstructions has shown the astounding seaworthiness and resilience of Viking trading ships and sailing ships. Could replicas do the same for the longship?

In 1963 Danish boy scouts built a replica of the Ladby ship. Observing that the warships depicted on the 11th-century Bayeux tapestry were used as horse transports, the young mariners wanted to see if horses could really clamber on board from a beach. Such a capability would have provided a motive for retaining the low freeboard throughout the Viking Age. The sea trials of the Ladby ship were a complete success, with horses, scouts and hull all performing well. The ship proved surprisingly swift and handy on the open sea, again vindic-

VIKING SHIPBUILDING METHODS were illustrated on the 11th-century Bayeux Tapestry (*top*) from the Musée de la Tapisserie in Bayeux, France. The techniques have been independently confirmed through reverse engineering (*bottom*). Marks on the original timbers proved that the primary tool was the broad ax, rather than the adze or saw.



SCALA/ART RESOURCE



VIKING SHIP MUSEUM, ROSKILDE

VIKING SHIP MUSEUM, ROSKILDE



RELATIVELY SLIGHT KEEL of a longship made for speedy portage. Here a team of horses pulls the *Helge Ask* over log rollers. The ease of portage enabled the 11th-century Norwegian King Magnus Barelegs to take advantage of a legal loophole. A

treaty with the king of Scotland granted Magnus all the land he could circumnavigate in his ship. The Norseman sailed to the Scottish peninsula of Kintyre and, sitting at the rudder, had his men drag him across the narrow neck of land so he could claim it.

cating the skill and ingenuity of the Viking shipwrights.

After the recovery of the Skuldelev ships in 1962, the Viking Ship Museum was built at Roskilde to house the remains and provide a center for study and reconstruction. In 1991 the Roskilde team built *Helge Ask*, an exact replica of the smaller (17-meter) Skuldelev longship and saw its predatory power in action. Even with only half the crew of 24 at the oars, the ship easily outrowed a replica of the smaller, broader trading ship, also found at Skuldelev (*Roar Ege*). The longship also outsailed the trader, with a working speed approaching eight knots.

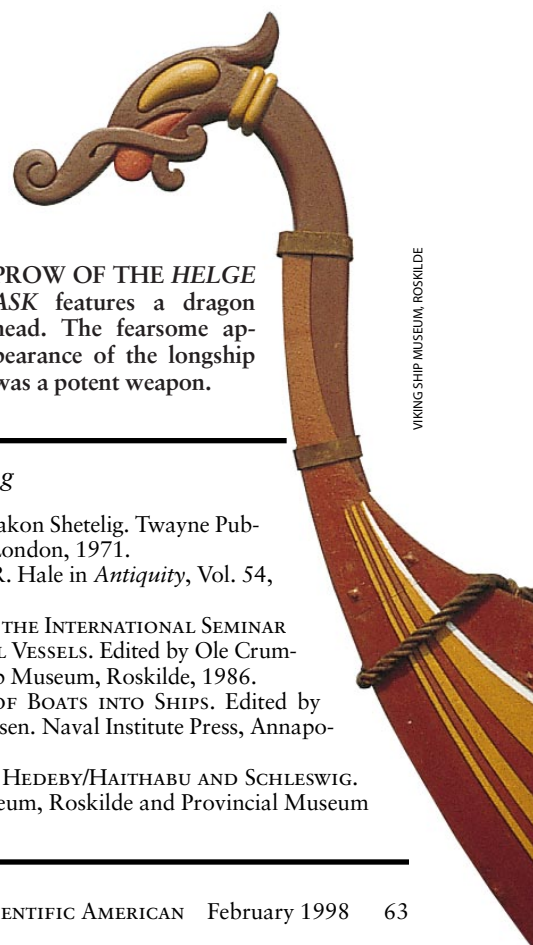
Although the trading ship performed better tacking into the wind, *Helge Ask's* crew could make up the difference by

quickly lowering sail and rowing. Crumlin-Pedersen calculates that the longship could overtake its prey in any conditions short of an outright gale. The sagas include an account of this capability: A Viking named Gauti Tófasen overtook four Danish knorrs in his longship. He was on the verge of capturing a fifth when a storm blew up, allowing his prey to escape.

In the past century more than 30 Viking ships have been reconstructed, and a host of neo-Vikings maintains and operates many of these replicas. At Roskilde, the guild of the *Helge Ask* takes the ship on sea trials and cruises in summer, hauls it overland to test portage accounts, repairs it during winter—and reports it all on the World Wide Web. A millennium after the building of the orig-

inal longships, the rough, expansive vigor of the Vikings is seaborne again. **SA**

Join host Alan Alda for a cruise on board the Helge Ask on this month's SCIENTIFIC AMERICAN FRONTIERS. For time and channel, check local listings.



PROW OF THE HELGE ASK features a dragon head. The fearsome appearance of the longship was a potent weapon.

VIKING SHIP MUSEUM, ROSKILDE

The Author

JOHN R. HALE, archaeologist and director of Liberal Studies at the University of Louisville, has conducted fieldwork in Scandinavia, Britain, Portugal, Greece and the Ohio River Valley. In the course of his doctoral research at the University of Cambridge, he studied boat designs found in Bronze Age Scandinavian art. He recognized that the vessels, commonly thought to be skin boats, were in fact wooden craft directly ancestral to the Viking longships. An oarsman himself, Hale has also reconstructed the rowing techniques used on the ancient Greek trireme (see the author's article in *Scientific American*, May 1996).

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The Theory Formerly Known as Strings

The Theory of Everything is emerging as one in which not only strings but also membranes and black holes play a role

by Michael J. Duff

At a time when certain pundits are predicting the End of Science on the grounds that all the important discoveries have already been made, it is worth emphasizing that the two main pillars of 20th-century physics, quantum mechanics and Einstein's general theory of relativity, are mutually incompatible. General relativity fails to comply with the quantum rules that govern the behavior of elementary particles, whereas on the opposite scale, black holes are challenging the very foundations of quantum mechanics. Something big has to give. This predicament augurs less the bleak future of diminishing returns predicted by the millennial Jeremiahs and more another scientific revolution.

Until recently, the best hope for a theory that would unite gravity with quantum mechanics and describe all physical phenomena was based on strings: one-dimensional objects whose modes of vibration represent the elementary particles. In the past two years, however, strings have been subsumed by M-theory. In the words of the guru of string theory (and according to *Life* magazine, the sixth most influential American baby boomer), Edward Witten of the Institute for Advanced Study in Princeton, N.J., "M stands for Magic, Mystery or Membrane, according to taste." New evidence in favor of this theory is appearing daily, representing the most exciting development since strings first swept onto the scene.

M-theory, like string theory, relies crucially on the idea of supersymmetry. Physicists divide particles into two classes, according to their inherent angular

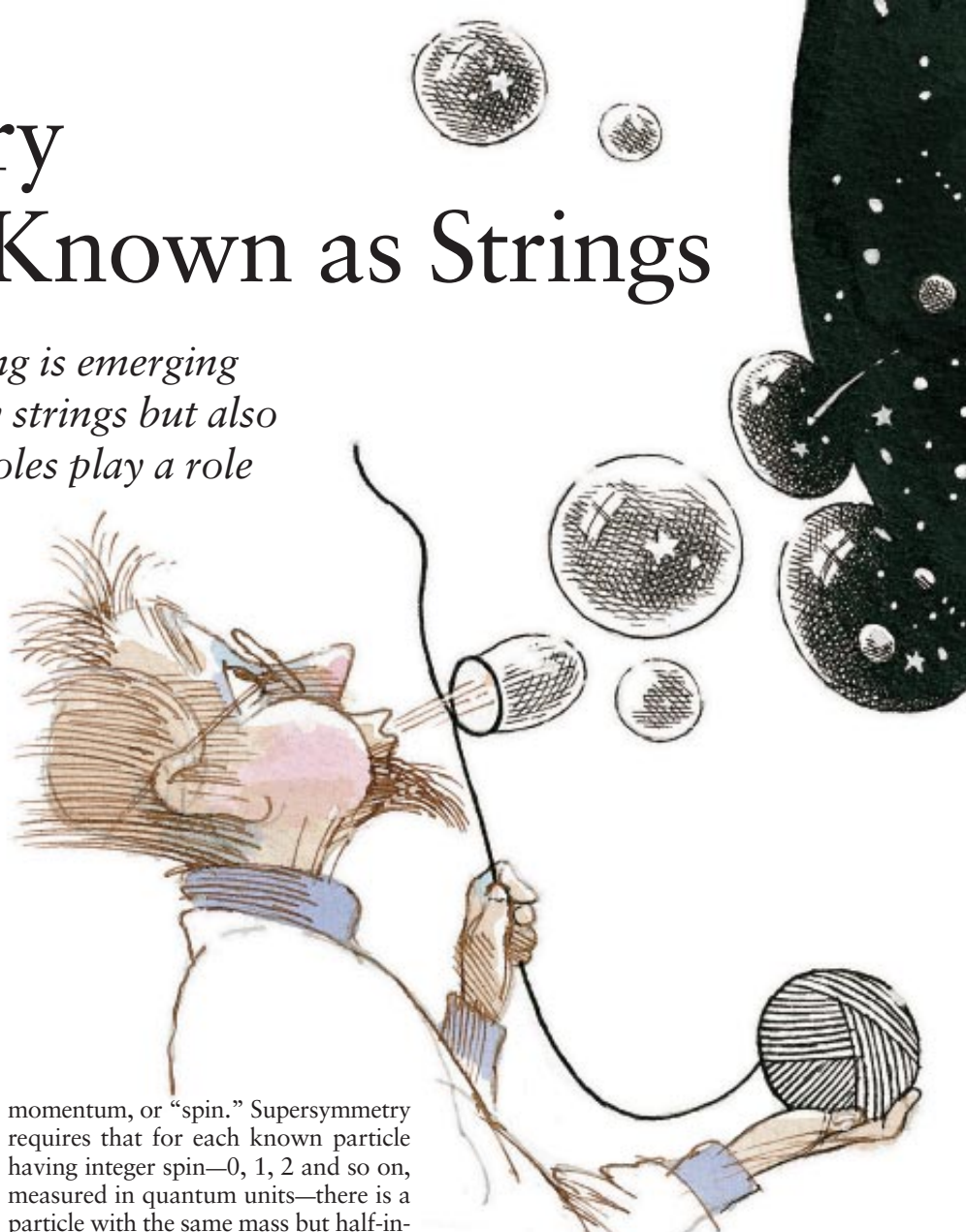
momentum, or "spin." Supersymmetry requires that for each known particle having integer spin—0, 1, 2 and so on, measured in quantum units—there is a particle with the same mass but half-integer spin ($1/2$, $3/2$, $5/2$ and so on), and vice versa.

Unfortunately, no such superpartner has yet been found. The symmetry, if it exists at all, must be broken, so that the postulated particles do not have the same mass as known ones but instead are too heavy to be seen in current accelerators. Even so, theorists have retained belief in supersymmetry primarily because it provides a framework within which the weak, electromagnetic and strong forces may be united with the most elusive force of all: gravity.

Supersymmetry transforms the coordinates of space and time such that the laws of physics are the same for all observers. Einstein's general theory of relativity derives from this condition, and so supersymmetry implies gravity. In fact, supersymmetry predicts "supergravity," in which a particle with a spin of 2—the graviton—transmits gravita-

tional interactions and has as a partner a gravitino, with a spin of $3/2$.

Conventional gravity does not place any limits on the possible dimensions of space-time: its equations can, in principle, be formulated in any dimension. Not so with supergravity, which places an upper limit of 11 on the dimensions of space-time. The familiar universe, of course, has three dimensions of space: height, length and breadth, while time makes up the fourth dimension of space-time. But in the early 1920s Polish physicist Theodore Kaluza and Swedish physicist Oskar Klein suggested that space-time may have a hidden fifth dimension. This extra dimension would not be infinite, like the others; instead it would close in on itself, forming a circle. Around that circle could reside quantum waves, fitting neatly into a loop. Only integer numbers of waves can fit around the circle; each of these would corre-





LIFE, THE UNIVERSE AND EVERYTHING may arise from the interplay of strings, bubbles and sheets in higher dimensions of space-time.

enabled string theory to sweep physicists off their feet and 11-dimensional supergravity into the doghouse. Murray Gell-Mann of the California Institute of Technology encapsulated the mood of the times by declaring at a meeting: "Eleven-dimensional supergravity—ugh!"

After the initial euphoria over strings, however, nagging doubts began to creep in. First, many important questions—especially how to confront the theory with experiment—seemed incapable of being answered by traditional methods of calculation. They called for radically new techniques. Second, why were there five different string theories? If one is looking for a unique Theory of Everything, surely this is an embarrassment of riches. Third, if supersymmetry permits 11 dimensions, why do superstrings stop at 10? Finally, if we are going to conceive of pointlike particles as strings, why not as membranes or more generally as p -dimensional objects—inevitably dubbed p -branes?

Consequently, while most theorists were tucking into super-spaghetti, a small but enthusiastic group were developing an appetite for super-ravioli. A particle, which has zero dimensions, sweeps out a one-dimensional trace, or "worldline," as it evolves in space-time [see illustration on next page]. Similarly a string—having one dimension, length—sweeps out a two-dimensional "worldsheet," and a membrane—having two dimensions, length and breadth—sweeps out a three-dimensional "worldvolume." In general, a p -brane sweeps out a world-volume of $p + 1$ dimensions. (Of course, there must be enough room for the p -brane to move about in space-time, so $p + 1$ must not exceed the number of space-time dimensions.)

As early as 1962, Paul A. M. Dirac, one of the fathers of quantum mechanics, had constructed an imaginative model based on a membrane. He postulated that the electron, instead of resembling a point, was in reality a minute bubble, a membrane closed in on itself. Its oscillations, Dirac suggested, might generate particles such as the muon, a heavier

spond to a particle with a different energy. So the energies would be "quantized," or discrete.

An observer living in the other four dimensions, however, would see a set of particles with discrete charges, rather than energies. The quantum, or unit, of charge would depend on the circle's radius. In the real world as well, electrical charge is quantized, in units of e , the charge on the electron. To get the right value for e , the circle would have to be tiny, about 10^{-33} centimeter in radius.

The unseen dimension's small size explains why humans, or even atoms, are unaware of it. Even so, it would yield electromagnetism, and gravity, already present in the four-dimensional world, would be united with that force.

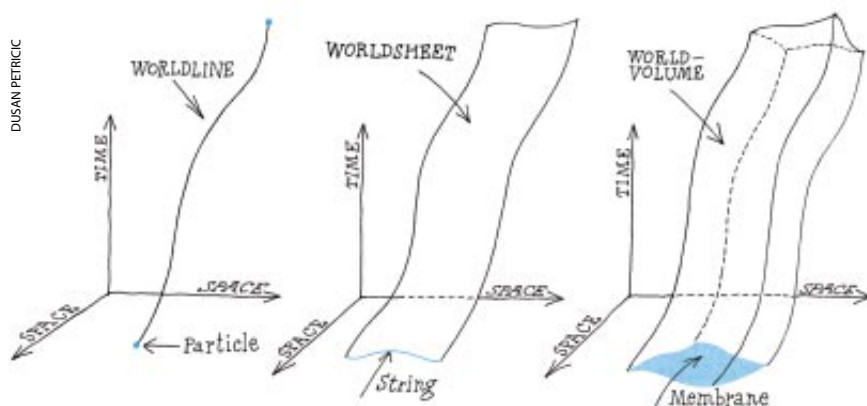
In 1978 Eugene Cremmer, Bernard Julia and Joel Scherk of the École Normale Supérieure in Paris realized that supergravity not only permits up to seven extra dimensions but is most elegant when existing in a space-time of 11 dimensions (10 of space and one of time). The kind of real, four-dimensional world the theory ultimately predicts depends on how the extra dimensions are rolled up, à la Kaluza and Klein. The several curled dimensions could conceivably allow physicists to derive, in addition to electromagnetism, the strong and weak nuclear forces. For these reasons, many physicists began to look to supergravity

in 11 dimensions in the hope that it might be the unified theory.

In 1984, however, 11-dimensional supergravity was rudely knocked off its pedestal. An important feature of the real world is that nature distinguishes between right and left: the laws governing the weak nuclear force operate differently when viewed through a mirror. (For instance, neutrinos always have left-handed spin.) But as Witten and others emphasized, such "handedness" cannot readily be derived by reducing space-time from 11 dimensions down to four.

P-Branes

Supergravity's position was usurped by superstring theory in 10 dimensions. Five competing theories held sway, designated by their mathematical characteristics as the $E_8 \times E_8$ heterotic, the $SO(32)$ heterotic, the $SO(32)$ Type I, the Type IIA and Type IIB strings. (The Type I is an "open" string consisting of just a segment, whereas the others are "closed" strings that form loops.) One string in particular, the $E_8 \times E_8$, seemed—at least in principle—capable of explaining the known elementary particles and forces, including their handedness. And unlike supergravity, strings seemed to provide a theory of gravity consistent with quantum effects. All these virtues



version of the electron. Although his attempt failed, the equations that Dirac postulated for the membrane are essentially the ones we use today. The membrane may take the form of a bubble, or it may be stretched out in two directions like a sheet of rubber.

Supersymmetry severely restricts the possible dimensions of a p-brane. In the space-time of 11 dimensions floats a membrane, discovered mathematically by Eric Bergshoeff of the University of Groningen, Ergin Sezgin, now at Texas A&M University, and Paul K. Townsend of the University of Cambridge. It has only two spatial dimensions and looks like a sheet. Paul S. Howe of King's College London, Takeo Inami of Kyoto University, Kellogg Stelle of Imperial College, London, and I were able to show that if one of the 11 dimensions is a circle, we can wrap the membrane around it once, pasting the edges together to form a tube. If the radius of the circle becomes sufficiently small, the rolled-up membrane ends up looking like a string in 10 dimensions; in fact, it yields precisely the Type IIA superstring.

Notwithstanding such results, the membrane enterprise was largely ignored by the orthodox string community. Fortunately, the situation was about to change because of progress in an apparently unrelated field.

In 1917 German mathematician Amalie Emmy Noether had shown that the mass, charge and other attributes of el-

ementary particles are generally conserved because of symmetries. For instance, conservation of energy follows if one assumes that the laws of physics remain unchanged with time, or are symmetric as time passes. And conservation of electrical charge follows from a symmetry of a particle's wave function.

Sometimes, however, attributes may be maintained because of deformations in fields. Such conservation laws are called topological, because topology is that branch of mathematics that concerns itself with the shape of things. Thus, it may happen that a knot in a set of field lines, called a soliton, cannot be smoothed out. As a result, the soliton is prevented from dissipating and behaves much like a particle. A classic example is a magnetic monopole—the isolated pole of a bar magnet—which has not been found in nature but shows up as twisted configurations in some field theories.

In the traditional view, then, particles such as electrons and quarks (which carry Noether charges) are seen as fundamental, whereas particles such as magnetic monopoles (which carry topological charge) are derivative. In 1977, however, Claus Montonen, now at the Helsinki Institute of Physics, and David I. Olive, now at the University of Wales at Swansea, made a bold conjecture. Might there exist an alternative formulation of physics in which the roles of Noether charges (like electrical charge)

TRAJECTORY of a particle in space-time traces a worldline. Similarly, that of a string or a membrane sweeps out a worldsheet or worldvolume, respectively.

and topological charges (like magnetic charge) are reversed? In such a “dual” picture, the magnetic monopoles would be the elementary objects, whereas the familiar particles—quarks, electrons and so on—would arise as solitons.

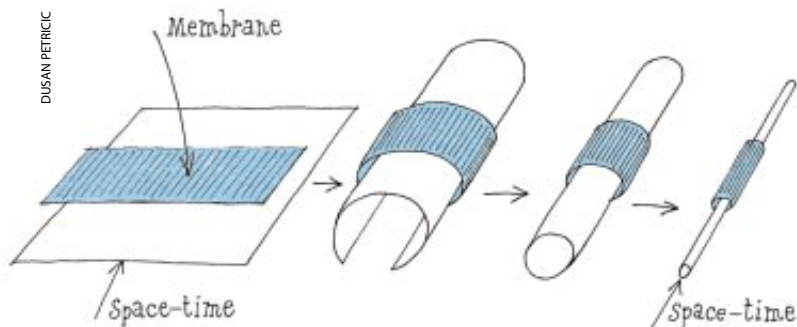
More precisely, a fundamental particle with charge e would be equivalent to a solitonic particle with charge $1/e$. Because its charge is a measure of how strongly a particle interacts, a monopole would interact weakly when the original particle interacts strongly (that is, when e is large), and vice versa.

The conjecture, if true, would lead to a profound mathematical simplification. In the theory of quarks, for instance, physicists can make hardly any calculations when the quarks interact strongly. But any monopoles in the theory must then interact weakly. One could imagine doing calculations with a dual theory based on monopoles and automatically getting all the answers for quarks, because the dual theory would yield the same final results.

Unfortunately, the idea remained on the back burner. It was a chicken-and-egg problem. Once proved, the Montonen-Olive conjecture could leap beyond conventional calculational techniques, but it would need to be proved by some other method in the first place.

As it turns out, p-branes can also be viewed as solitons. In 1990 Andrew Strominger of the Institute for Theoretical Physics in Santa Barbara found that a 10-dimensional string can yield a soliton that is a five-brane. Reviving an earlier conjecture of mine, Strominger suggested that a strongly interacting string is the dual equivalent of weakly interacting five-branes.

There were two major impediments to this duality. First, the duality proposed by Montonen and Olive—between electricity and magnetism in ordinary four dimensions—was still unproved, so duality between strings and



SIMULTANEOUS SHRINKING of a membrane and a dimension of space-time can result in a string. As the underlying space, shown here as a two-dimensional sheet, curls into a cylinder, the membrane wraps around it. The curled dimension becomes a circle so small that the two-dimensional space ends up looking one-dimensional, like a line. The tightly wrapped membrane then resembles a string.

EXTRA DIMENSION curled into a tube offers insights into the fabric of space-time.



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five-branes in 10 dimensions was even more tenuous. Second, there were all kinds of issues about how to find the quantum properties of five-branes and hence how to prove the new duality.

The first of these impediments was removed, however, when Ashoke Sen of the Tata Institute of Fundamental Research in Bombay established that supersymmetric theories would require the existence of certain solitons with both electrical and magnetic charges. These objects had been predicted by the Montonen-Olive conjecture. This seemingly inconspicuous result converted many skeptics and unleashed a flood of papers. In particular, it inspired Nathan Seiberg of Rutgers University and Edward Witten to look for duality in more realistic (though still supersymmetric) versions of quark theories. They provided a wealth of information on quantum fields, of a kind unthinkable just a few years ago.

Duality of Dualities

In 1990 several theorists generalized the idea of Montonen-Olive duality to four-dimensional superstrings, in whose realm the idea becomes even more natural. This duality, which nonetheless remained speculative, goes by the name of S-duality.

In fact, string theorists had already been used to a totally different kind of duality called T-duality. T-duality relates two kinds of particles that arise when a string loops around a compact dimension. One kind (call them “vibrating” particles) is analogous to those predicted by Kaluza and Klein and comes from vibrations of the loop of string [see illustration on next page]. Such particles are more energetic if the circle is small. In addition, the string can wind many times around the circle,

like a rubber band on a wrist; its energy becomes higher the more times it wraps around and the larger the circle. Moreover, each energy level represents a new particle (call them “winding” particles).

T-duality states that the winding particles for a circle of radius R are the same as the “vibration” particles for a circle of radius $1/R$, and vice versa. To a physicist, the two sets of particles are indistinguishable: a fat, compact dimension may yield apparently the same particles as a thin one.

This duality has a profound implication. For decades, physicists have been struggling to understand nature at the extremely small scales near the Planck length of 10^{-33} centimeter. We have always supposed that laws of nature, as we know them, break down at smaller distances. What T-duality suggests, however, is that at these scales, the universe looks just the same as it does at large scales. One may even imagine that if the universe were to shrink to less than the Planck length, it would transform into a dual universe that grows bigger as the original one collapses.

Duality between strings and five-branes still remained conjectural, however, because of the problem of quantizing five-branes. Starting in 1991, a team at Texas A&M, involving Jianxin Lu, Ruben Minasian, Ramzi Khuri and myself, solved the problem by sidestepping it. If four of the 10 dimensions curl up and the five-brane wraps around these, the latter ends up as a one-dimensional object—a (solitonic) string in six-dimensional space-time. In addition, a fundamental string in 10 dimensions remains fundamental even in six di-

“BRANE” SCAN lists the membranes that arise in space-times of different dimensions. A p-brane of dimension 0 is a particle, that of dimension 1 is a string and that of dimension 2 is a sheet or bubble. Some branes have no spin (red), but Dirichlet-branes have spin of 1 (blue).

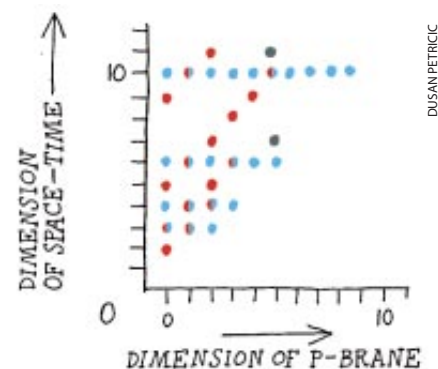
mensions. So the concept of duality between strings and five-branes gave way to another conjecture, duality between a solitonic and a fundamental string.

The advantage is that we do know how to quantize a string. Hence, the predictions of string-string duality could be put to the test. One can show, for instance, that the strength with which the solitonic strings interact is given by the inverse of the fundamental string’s interaction strength, in complete agreement with the conjecture.

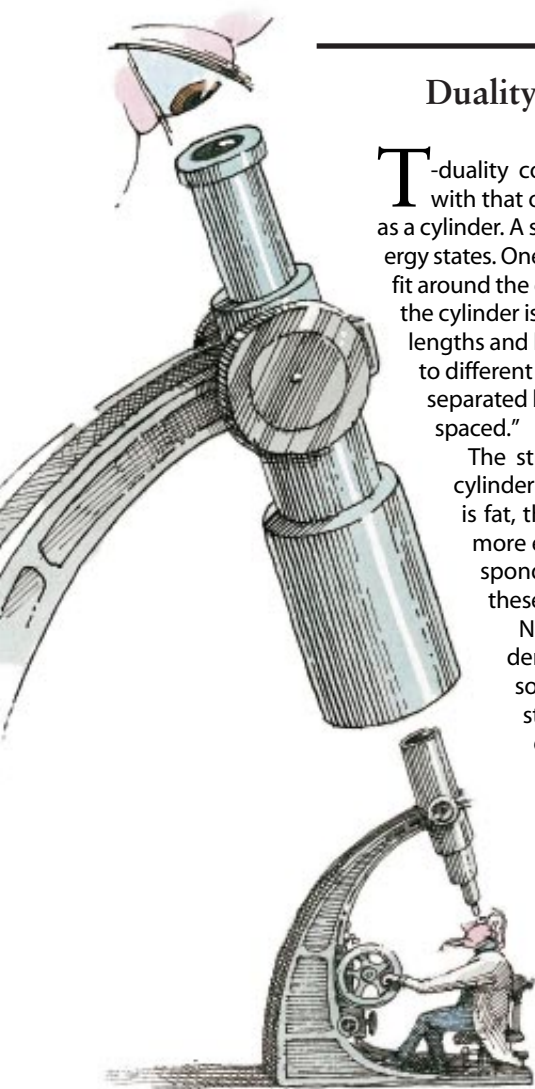
In 1994 Christopher M. Hull of Queen Mary and Westfield College, along with Townsend, suggested that a weakly interacting heterotic string can even be the dual of a strongly interacting Type IIA string, if both are in six dimensions. The barriers between the different string theories were beginning to crumble.

It occurred to me that string-string duality has another unexpected payoff. If we reduce the six-dimensional space-time to four dimensions, by curling up two dimensions, the fundamental string and the solitonic string each acquire a T-duality. But here is the miracle: the T-duality of the solitonic string is just the S-duality of the fundamental string, and vice versa. This phenomenon—in which the interchange of charges in one picture is just the inversion of length in the dual picture—is called the Duality of Dualities. It places the previously speculative S-duality on just as firm a footing as the well-established T-duality. In addition, it predicts that the strength with which objects interact—their charges—is related to the size of the invisible dimensions. What is charge in one universe may be size in another.

In a landmark talk at the University of Southern California in 1995, Witten suddenly drew together all the work on T-duality, S-duality and string-string duality under the umbrella of M-theory in 11 dimensions. In the following months, literally hundreds of papers appeared



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Duality between Large and Small

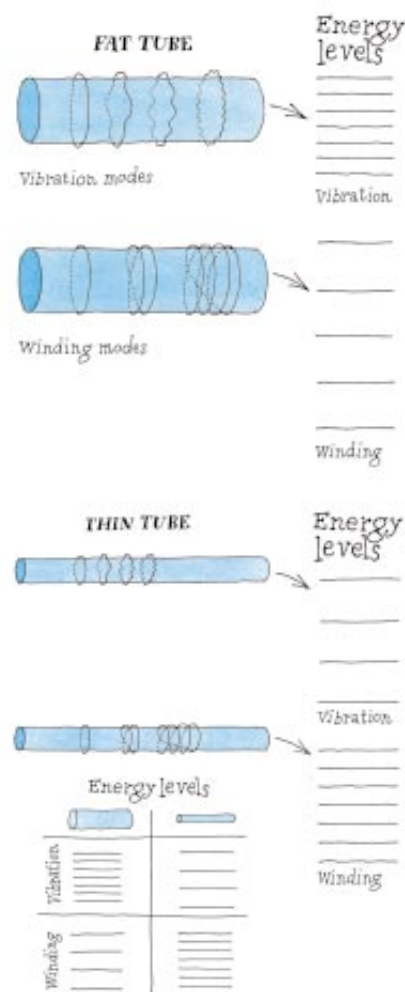
T-duality connects the physics of large space-times with that of small ones. Visualize a curled space-time as a cylinder. A string looped around it has two kinds of energy states. One set arises from the waves in the string that fit around the cylinder; call these the “vibration” modes. If the cylinder is fat, the vibrations tend to have long wavelengths and less energy. So the energies corresponding to different numbers of waves around the cylinder are separated by small amounts—that is, they are “closely spaced.”

The string can, however, also loop around the cylinder like a stretched rubber band. If the cylinder is fat, the string needs to stretch more, requiring more energy. So the energies of the states corresponding to different numbers of loops—call these the “winding” modes—are widely spaced.

Now look at the energy levels for a thin cylinder. The waves fitting around it are small and so have high energy. As a result, the vibration states are widely spaced. But the loops require less energy, and so the winding modes are closely spaced.

To an outside observer, however, the different physical origins of the vibration and winding states are not apparent. Both the thin and the fat tube yield ultimately the same energy levels, which physicists interpret as particles. Thus, the minute scales of the thin space-time may yield exactly the same physics as the large scales of our universe.

—M.J.D.



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on the Internet confirming that whatever M-theory may be, it certainly involves membranes in an important way.

Even the $E_8 \times E_8$ string, whose handedness was thought impossible to derive from 11 dimensions, acquired an origin in M-theory. Witten, along with Petr Horava of Princeton University, showed how to shrink the extra dimension of M-theory into a segment of a line. The resulting picture has two 10-dimensional universes (each at an end of the line) connected by a space-time of 11 dimensions. Particles—and strings—exist only in the parallel universes at the ends, which can communicate with each other only via gravity. (One can speculate that all visible matter in our universe lies on one wall, whereas the “dark matter,” believed to account for the invisible mass in the universe, resides in a parallel universe on the other wall.)

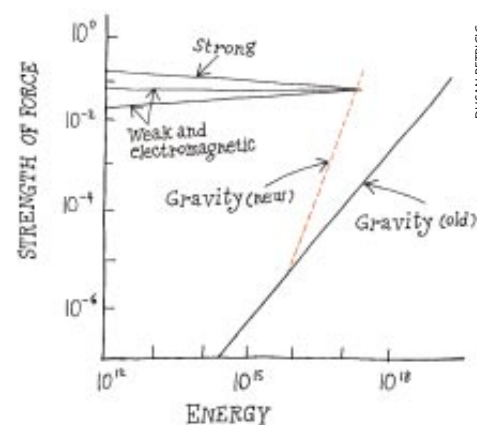
This scenario may have important consequences for confronting M-theory with experiment. For example, physi-

cists know that the intrinsic strengths of all the forces change with the energy of the relevant particles. In supersymmetric theories, one finds that the strengths of the strong, weak and electromagnetic forces all converge at an energy E of 10^{16} giga electron volts. Further, the interaction strengths almost equal—but not quite—the value of the dimensionless number GE^2 , where G is Newton’s gravitational constant. This near miss, most likely not a coincidence, seems to call for an explanation; it has been a source of great frustration for physicists.

But in the bizarre space-time envisioned by Horava and Witten, one can

THREE FORCES CONVERGE to the same strength when particles are as energetic as 10^{16} giga electron volts. Until now, gravity was believed to miss this meeting point. But calculations including the 11th dimension of M-theory suggest that gravity as well may converge to the same point.

choose the size of the 11th dimension so that all four forces meet at this common scale. It is far less than the Planck energy of 10^{19} giga electron volts, at which gravity was formerly expected to become strong. (High energy is connected to small distance via quantum mechanics. So Planck energy is simply Planck length expressed as energy.) So quantum-gravitational effects may be



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far closer in energy to everyday events than physicists previously believed, a result that would have all kinds of cosmological consequences.

Recently Joseph Polchinski of the Institute for Theoretical Physics at Santa Barbara realized that some p-branes resemble a surface discovered by 19th-century German mathematician Peter G. L. Dirichlet. On occasion these branes can be interpreted as black holes or, rather, black-branes—objects from which nothing, not even light, can escape.

Open strings, for instance, may be regarded as closed strings, part of which are hidden behind the black-branes. Such breakthroughs have led to a new interpretation of black holes as intersecting black-branes wrapped around seven curled dimensions. As a result, there are strong hints that M-theory may even clear up the paradoxes of black holes raised by Stephen W. Hawking of the University of Cambridge.

In 1974 Hawking showed that black holes are in fact not entirely black but may radiate energy. In that case, black holes must possess entropy, which measures the disorder of a system by accounting for the number of quantum states available. Yet the microscopic origin of these quantum states stayed a mystery. The technology of Dirichlet-branes has now enabled Strominger and Cumrun Vafa of Harvard University to count the number of quantum states in black-branes. They find an entropy that agrees perfectly with Hawking's prediction, placing another feather in the cap of M-theory.

Black-branes also promise to solve one of the biggest problems of string theory: there seem to be billions of different ways of crunching 10 dimensions down to four. So there are many competing predictions of how the real world works—in other words, no prediction at all. It turns out, however, that the mass

of a black-brane can vanish as a hole it wraps around shrinks. This feature miraculously affects the space-time itself, allowing one space-time with a certain number of internal holes (resembling a Gruyère cheese) to change to another with a different number of holes, violating the laws of classical topology.

If all the space-times are thus related, finding the right one becomes a more tractable problem. The string may ultimately choose the space-time with, say, the lowest energy and inhabit it. Its undulations would then give rise to the elementary particles and forces as we know them—that is, the real world.

10 to 11: Not Too Late

Despite all these successes, physicists are glimpsing only small corners of M-theory; the big picture is still lacking. Recently Thomas Banks and Stephen H. Shenker of Rutgers University, together with Willy Fischler of the University of Texas and Leonard Susskind of Stanford University, have proposed a rigorous definition of M-theory. Their “matrix” theory is based on an infinite number of zero-branes (particles, that is). The coordinates, or positions, of these particles, instead of being ordinary numbers, are matrices that do not com-

mute—that is, xy does not equal yx . In this picture space-time itself is a fuzzy concept in which the coordinates cannot be defined as the usual numbers but instead as matrices.

Physicists have long suspected that unifying gravity—in other words, the geometry of space-time—with quantum physics will lead to space-time becoming similarly ill defined—at least until a new definition is discovered. The matrix approach has generated great excitement but does not yet seem to be the last word. Over the next few years, we hope to discover what M-theory really is.

Witten is fond of imagining how physics might develop on another planet, where major discoveries such as general relativity, quantum mechanics and supersymmetry are made in a different order than on Earth. In a similar vein, I would like to suggest that on planets more logical than ours, 11 dimensions would have been the starting point from which 10-dimensional string theory was subsequently derived. Indeed, future terrestrial historians may judge the late 20th century as a time when theorists were like children playing on the seashore, diverting themselves with the smoother pebbles or prettier shells of superstrings while the great ocean of M-theory lay undiscovered before them.

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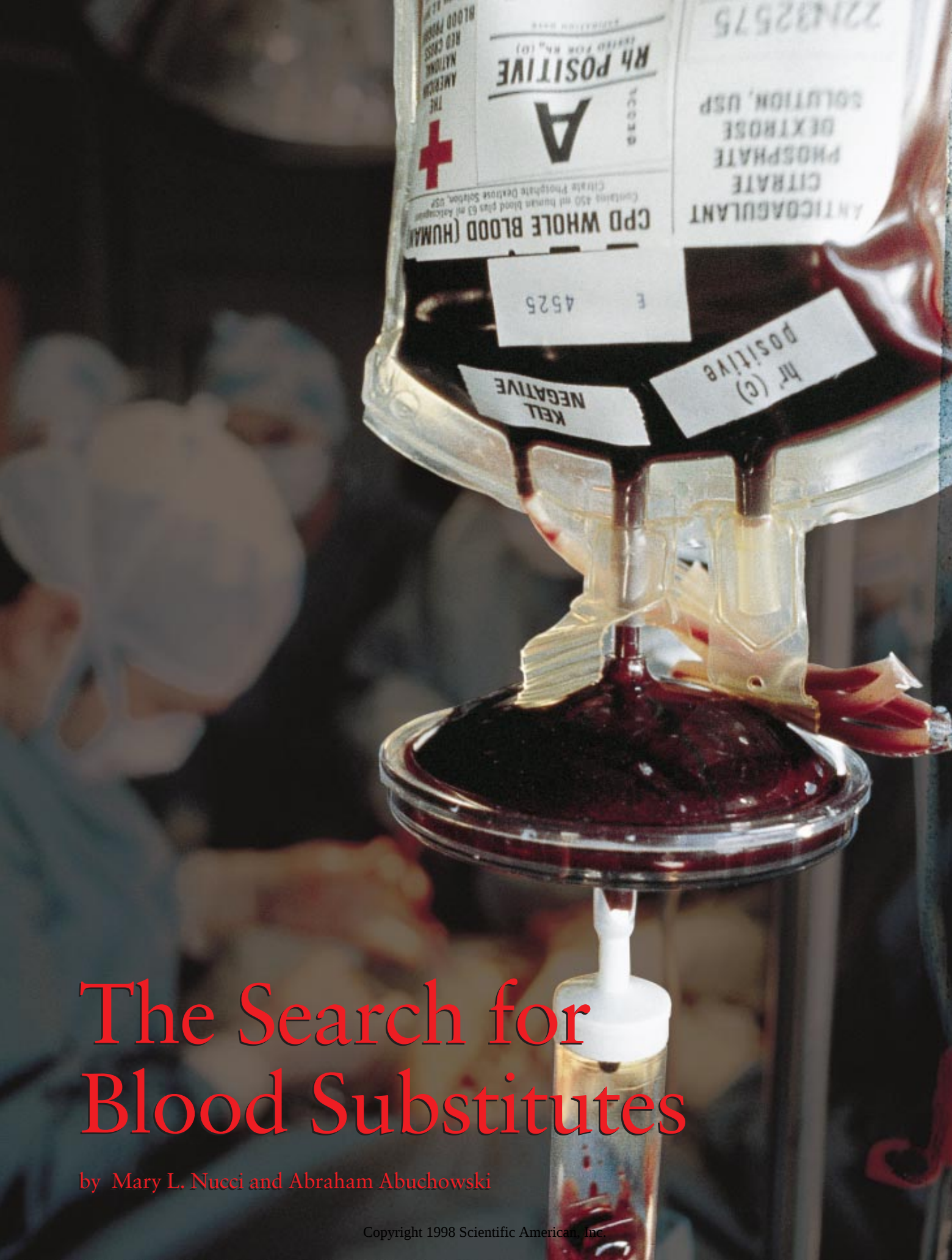
M-THEORY in 11 dimensions gives rise to the five string theories in 10 dimensions. When the extra dimension curls into a circle, M-theory yields the Type IIA superstring, which is further related by duality to the Type IIB string. If, however, the extra dimension shrinks to a line segment, M-theory becomes the physically plausible $E_8 \times E_8$ heterotic string. The latter is connected to the $SO(32)$ string theories by dualities.

The Author

MICHAEL J. DUFF conducts research on unified theories of elementary particles, quantum gravity, supergravity, superstrings, supermembranes and M-theory. He earned his Ph.D. in theoretical physics in 1972 at Imperial College, London, and joined the faculty there in 1980. He moved to the U.S. in 1988 and has been a Distinguished Professor at Texas A&M University since 1992. Duff has acted as a spokesperson for British Scientists Abroad, a group of expatriate scientists concerned about the underfunding of British science and the consequent brain drain. He is a Fellow of the American Physical Society.

Further Reading

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The Search for Blood Substitutes

by Mary L. Nucci and Abraham Abuchowski

The threat of global shortages of blood and fears about contamination have hastened attempts to find life-sustaining alternatives. Several of these compounds look promising

In the mid-1980s blood became a bad word. Reports that HIV—the human immunodeficiency virus, which causes AIDS—was being transmitted through transfusions led to general panic among the public and to the institution of new massive screening procedures for U.S. blood banks. In some places, including France, certain physicians maintained that the blood supply was safe—when, tragically, it was not. As a consequence, fear has not abated. Although the chance of contracting HIV through a transfusion is between one in 450,000 and one in a million, the perception remains that most blood is tainted.

This reputation, ill deserved as it may be, is one of the two major problems facing blood banks today. The second dilemma concerns supply. In the U.S., a country where someone requires a transfusion every three seconds or so, the number of blood donors continues to fall: no more than 5 percent of the population now gives blood. At the same time, the group of people who most often require transfusions, the elderly, is growing. Although estimates vary, it appears that every year the world needs 7.5 million more liters of blood; by 2030, experts anticipate there will be an annual shortfall of four million units (a unit is 500 milliliters) in the U.S.

For these reasons and others, the race is on to find blood substitutes. Although researchers have been investigating the possibilities since the 1950s, efforts redoubled after the Food and Drug Administration, the National Institutes of Health and the Department

of Defense held large conferences in the 1980s on the need to develop such compounds. Scientists at several institutions and six companies have already developed substitutes. But although there is great progress and hope, the challenges remain enormous. A decade into the campaign, no perfect solution is visible on the horizon. It is, after all, the essence of life that these investigators, ourselves among them, are trying to understand and manufacture.

The Heart of the Matter

Blood is as complex as the challenge of finding a substitute suggests. It is made up of blood cells, salts and other substances, such as proteins and vitamins, that are suspended in plasma. The three kinds of blood cells—red cells, white cells and platelets—comprise about 45 percent of the volume of blood: normally, a cubic centimeter of human blood contains between 4.5 million and 5.5 million red cells, between 7,000 and 12,000 white cells, and between 150,000 and 400,000 platelets.

This complex of cells and compounds performs myriad tasks: blood transports nutrients, hormones and waste products; it defends the body against infection; and its ability to clot prevents blood loss. Yet by far the most familiar function of blood is its role in respiration and its capture and release of oxygen and carbon dioxide. The protein hemoglobin—250 million molecules of which can be found inside each red blood cell—is the key to this process.

The most common protein in blood, hemoglobin is found in most vertebrates and has been conserved through evolution—that is, it looks remarkably similar in different species and is always composed of four polypeptide chains. In humans, hemoglobin consists of two identical alpha and two identical beta chains, each one about 140 amino acids long. An alpha binds strongly to a beta, creating a dimer; the two alpha-beta dimers

then bind weakly to each other, creating a tetramer.

Each of these polypeptide chains contains a heme unit, which, in turn, contains a molecule of iron. These iron atoms are the binding sites for oxygen; thus, each molecule of hemoglobin can bind four molecules of oxygen. Hemoglobin picks up oxygen in the lungs and transports it throughout the body. The more oxygen the hemoglobin molecule binds, the more adept it becomes at picking up the gas. This is because grabbing a molecule of oxygen changes the shape of the hemoglobin molecule; this change in configuration literally opens hemoglobin to more oxygen, until the four iron molecules are filled. Once the oxygen is released from the hemoglobin in various parts of the body, the red blood cells pick up carbon dioxide—a waste product of cellular respiration—which travels through the blood to the lungs, where it is released and, ultimately, exhaled.

Hemoglobin can also pick up other gases. For instance, researchers recently discovered that hemoglobin can transport nitric oxide. Nitric oxide has an important role in, among many other functions, maintaining blood pressure [see “Biological Roles of Nitric Oxide,” by Solomon H. Snyder and David S. Bredt; *SCIENTIFIC AMERICAN*, May 1992]. Hemoglobin thereby serves as a vital shuttle, carrying gases that are essential both to the body and to its own smooth functioning.

Lifeblood

Obviously, severe blood loss threatens many important processes. If people lose 30 to 40 percent of their blood, their bodies can compensate by quickly producing red blood cells, by moving blood away from nonessential organs and by shunting fluid into circulation in order to restore blood volume. But, depending on the age and health of the individual, once a person loses more

TRANSFUSION must occur once a person has lost more than 40 percent of his or her blood. In the U.S. alone, a transfusion takes place about every three seconds—and some 12 million units of blood are used every year. As the population ages, the need for transfusions is increasing; by 2030, there will be an estimated shortage of four million units of blood.

than 40 percent of his or her blood, a transfusion is generally needed.

Transfusions have a long, somewhat murky history. Various fluids have been tried throughout the centuries, including ale, urine, opium, plant resins, milk and sheep's blood. In 1667 Jean-Baptiste Denis, a physician to Louis XIV, performed the first documented, successful human-to-human blood transfusion. The procedure was banned in France—as well as in Rome and England shortly thereafter—when the wife of one of Denis's transfusion patients sued him. It turned out that the man had died not as a result of transfusion but rather because his wife had poisoned him with arsenic. Nevertheless, the reputation of transfusions had been tarnished. Per-

haps for good reason, because those that were performed resulted as frequently in death as they did in prolonged life.

Medical interest in the procedure did not really reawaken until the early 1900s, when Austrian-American pathologist Karl Landsteiner discovered the ABO blood group system and greatly improved the success of transfusions. Landsteiner found that two sugars—he called them A and B—can adorn the surface of red blood cells and that each individual has some combination, or lack, of these two sugars. Today physicians know that there are four such combinations and, hence, blood types. If these types are mixed during a transfusion, antibodies found in the bloodstream of the patient react against the sugars,

which are called antigens, on the surface of the donor's red blood cells. This reaction causes tiny clots, hemolysis (when hemoglobin leaks out of red blood cells) and, subsequently, death.

Matching must therefore be precise. Type A can be given to a person with A or AB blood; type B to someone with B or AB blood; and AB can be given only to another AB type. Type O, which has neither A nor B antigens, can be given to anyone—making those with O universal donors—but type O individuals can accept only O. Finally, AB types are universal acceptors: they can receive A, B, AB or O.

Blood typing must also account for the Rh groups. Working with rhesus monkeys in the 1940s, researchers discov-

PLASMA (55 PERCENT)

CELLS (45 PERCENT)

THE COMPOSITION OF BLOOD	
CONSTITUENT	MAJOR FUNCTION
WATER	SOLVENT FOR CARRYING OTHER SUBSTANCES
SALTS SODIUM, POTASSIUM, CALCIUM, MAGNESIUM, CHLORIDE, BICARBONATE	OSMOTIC BALANCE, pH BUFFERING, REGULATION OF MEMBRANE PERMEABILITY
PLASMA PROTEINS ALBUMIN FIBRINOGEN IMMUNOGLOBULINS	OSMOTIC BALANCE, pH BUFFERING CLOTTING DEFENSE (ANTIBODIES)
CELL TYPE	CELL FUNCTION
ERYTHROCYTES (RED BLOOD CELLS) 5 TO 6 MILLION PER CUBIC MILLIMETER OF BLOOD 	TRANSPORT OXYGEN AND HELP TO TRANSPORT CARBON DIOXIDE
LEUKOCYTES (WHITE BLOOD CELLS) 5,000 TO 10,000 PER CUBIC MILLIMETER OF BLOOD BASOPHIL NEUTROPHIL EOSINOPHIL MONOCYTE LYMPHOCYTE	PRODUCTION OF ANTIBODIES FOR DEFENSE AGAINST INFECTION
PLATELETS 250,000 TO 400,000 PER CUBIC MILLIMETER OF BLOOD 	BLOOD CLOTTING
SUBSTANCES TRANSPORTED BY BLOOD	
NUTRIENTS (FOR EXAMPLE, GLUCOSE, FATTY ACIDS, VITAMINS), WASTE PRODUCTS OF METABOLISM, RESPIRATORY GASES (OXYGEN AND CARBON DIOXIDE), HORMONES	

SOURCE: *Biology*, by Neil Campbell © 1990

MANY TASKS performed by blood account for the fluid's complexity. Made of almost equal parts plasma and cells, blood orchestrates the transport of nutrients and chemical messengers, while regulating respiration, clotting and immune function.

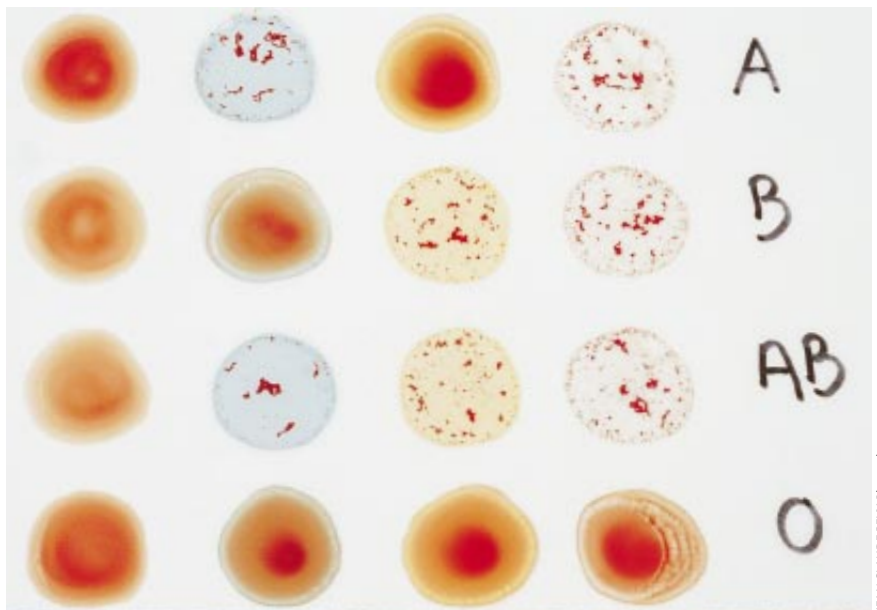
ered that blood can have an Rh antigen, in which case it is called Rh+. Absent that antigen, the blood is labeled Rh-. Transfusions must give Rh+ blood only to Rh+ patients; Rh- blood, however, can be given to both Rh+ and Rh- individuals.

More than 23 million units of blood are transfused each year, the American Association of Blood Banks reports. The risk of dying from a blood transfusion is about one in 100,000—as compared with a two-in-100,000 chance of dying in a car accident or a one-in-10,000 chance of dying from influenza. This risk includes the possibility of blood-typing errors as well as infection from bacteria and viruses. As noted earlier, transfusions have contained HIV. As of June 1997, 8,450 people had developed AIDS as the result of contaminated blood, according to the Centers for Disease Control and Prevention; this number does not reflect actual infection, because AIDS symptoms take years to develop. Transfusions can also introduce various forms of the hepatitis virus. A recent study in the *New England Journal of Medicine* states that a person has a one-in-63,000 chance of contracting hepatitis B and a one-in-103,000 chance for hepatitis C.

The Two Paths

A successful blood substitute has to meet a minimum, but hefty, set of requirements. It has to be nontoxic, free from disease and easily transportable; it cannot elicit an immune response; and it has to work for all blood types. The compound also has to remain in circulation until the body is able to restore its own blood, and then it should be excreted without side effects. Because storage is so difficult and expensive—blood must be kept at four degrees Celsius, and, even then, it stays fresh for a maximum of 42 days—a good substitute should have a long shelf life. And, if it were to be ideal, the mimic would perform blood's many tasks.

Blood substitutes on or coming on the market seek to meet all these requirements except the last; they focus only on reproducing blood's most basic duty—that of transporting oxygen. (They differ from what are called volume expanders—such as saline, plasma or dextrose solution—which have been developed simply to increase blood volume, not to restore any of its other functions.) Over the years, two major approaches to developing blood substitutes have emerged:



JEAN CLAUDE REWY Phototake

BLOOD TYPE is defined by the presence or absence of antigens—A, B and Rh—on the surface of red blood cells. Type A blood is so called because it carries antigen A, type B carries only B, type AB has both and type O has neither. In addition, blood is termed Rh+ if it has the Rh antigen; otherwise it is Rh-. Blood must be carefully matched so that a transfusion does not provoke a fatal immune reaction in the patient.

one is based on chemicals; the other relies on hemoglobin.

Proponents of the chemical-based solution rely on synthetic oxygen-carrying compounds, known as perfluorocarbons (PFCs)—compounds similar to Teflon. Advocates of the hemoglobin-based strategy argue that blood's ability to capture and transport gases can be reproduced only by using the real thing. (Other research is ongoing but has not yet yielded any products that are in clinical trials, including the production of hemoglobin in transgenic animals, the alteration of the surface of red blood cells to produce universal donor red cells, the freeze-drying of red blood cells and the encapsulation of hemoglobin into liposomes—or so-called neo red cells.)

PFCs can dissolve large quantities of gases such as oxygen and carbon dioxide. They were made famous in the 1960s, when Leland Clark of the University of Alabama showed that a mouse immersed in PFC liquid could breathe relatively normally. A more recent example figured in the 1989 movie *The Abyss*, in which a character survives a deep-ocean dive by “breathing” an oxygen-carrying liquid. Because they are inert and will not dissolve in plasma, PFCs being developed today must be emulsified with an agent that permits them to form particles that can then disperse in blood.

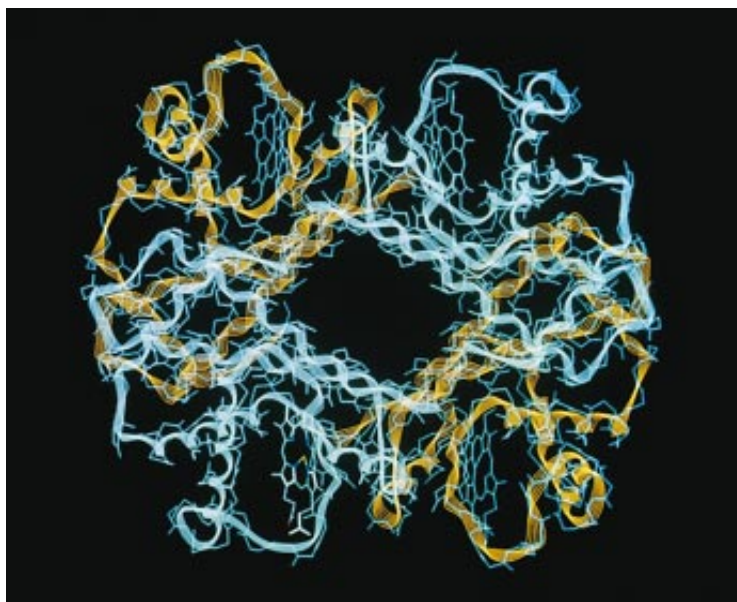
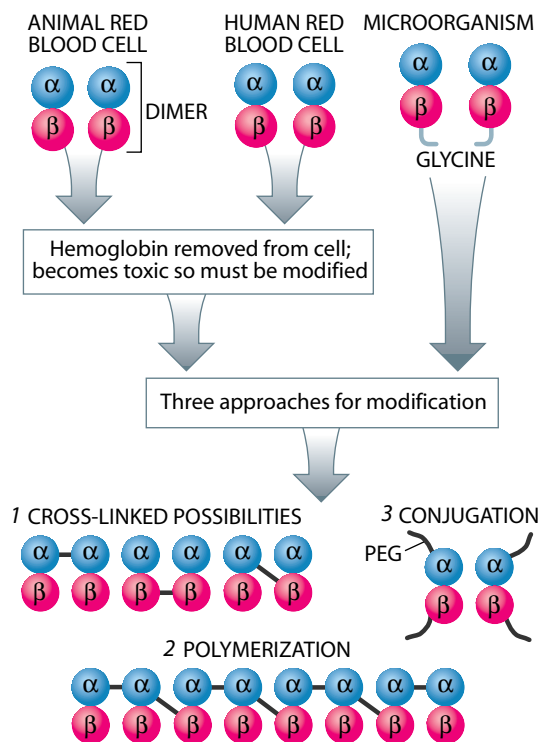
Unlike hemoglobin—which actively grabs and frees the oxygen—perfluorocarbons deliver gas passively. Oxygen from the lungs moves directly to the PFCs that are floating in the plasma, bypassing the red blood cells; the PFCs then travel to the rest of the body, where they diffuse out in the capillaries, exchanging oxygen for carbon dioxide.

One benefit of PFCs is that the amount of oxygen they can pick up is directly proportional to the amount of oxygen breathed in. So a patient can be given gas with a higher partial pressure of oxygen than is found in room air, and the PFCs can absorb and transport more of it. PFCs can also transfer gases quickly, because the gases do not have to diffuse across the membrane of a red blood cell. Hemoglobin molecules, on the other hand, can carry only four molecules of oxygen at any one time—regardless of the amount of oxygen available—and the gas must move across the blood cell membrane.

PFCs are cleared from the circulation by the reticuloendothelial system, which stores the droplets in the spleen and liver until they are exhaled as vapor by the lungs. The droplets are cleared within four to 12 hours of injection of PFCs into the body, but little is known about the long-term effects of PFC retention.

When PFCs were first used as blood substitutes in mice in the 1960s, they

SOURCES OF HEMOGLOBIN



JEAN-CLAUDE REWY Photostock

HEMOGLOBIN-BASED SUBSTITUTES take one of three forms. Hemoglobin (*above*) gathered from humans or animals—or from organisms genetically engineered to produce it—can be toxic when not housed in a red blood cell. So researchers cross-link (1), polymerize (2) or attach polyethylene glycol, or PEG (3), to render the hemoglobin safe. Any of these configurations can be used to make blood substitutes.

had a serious drawback: they were not well excreted and would accumulate in body tissues. In the 1980s, however, a new version of PFC entered clinical development. This compound, Fluosol-DA (made by Green Cross Corporation in Osaka, Japan), was approved in the U.S. for use in select patients, including some who refuse blood transfusions because of religious beliefs. But storage complications, side effects and low efficacy prevented it from achieving widespread use.

The next set of PFC-based substitutes, designed to overcome these problems, is currently in clinical development. One called Oxygent (made by Alliance Pharmaceutical Corporation in San Diego) has a shelf life of two years if it is refrigerated. Other, newer PFCs deliver up to four times as much oxygen as their earlier versions did. Yet increasing the oxygen-carrying capacity of blood can lead to the accumulation of oxygen in tissues, which, in turn, can cause damage. Clinical studies of PFC-based substitutes are under way, and researchers are trying to find ways to reduce side effects.

By far the greatest number of researchers working on blood substitutes have focused on manipulating the structure of hemoglobin. Apparently, the compound was tested as a blood substitute as early as 1868, when an experi-

menter injected dogs with hemoglobin. The results were not promising. The dogs became ill and suffered severe kidney damage, and their blood's ability to transport oxygen decreased. It became apparent that when the dog's hemoglobin was naked—that is, it lacked the envelope of the red blood cell—it became unstable. It broke down into its dimers, passed into the kidneys, where it caused damage, and was finally excreted in just a few hours. The subunits were so small that they could not be filtered by the renal system or returned to the body.

Looking to Hemoglobin

The same problems can arise with human hemoglobin. To be effective, hemoglobin must contain a compound known as 2,3-diphosphoglycerate (2,3-DPG), which is present only in red blood cells. Without 2,3-DPG, hemoglobin binds oxygen in the lungs but will not release it elsewhere in the body. Without 2,3-DPG and other elements of red blood cells, hemoglobin is also prone to auto-oxidation—during which the iron atoms change state and irreversibly lose their ability to bind gas molecules.

In 1969 scientists discovered that they could reverse this process by chemically modifying unbound hemoglobin. At this point, it again became possible to

consider using the compound as a blood substitute. Researchers have subsequently found several modifications effective: cross-linking alpha-alpha, beta-beta or alpha-beta chains; polymerization of hemoglobin molecules; or conjugation with a polymer called polyethylene glycol (PEG), a compound found in some foods and cosmetics. Because modification usually increases the size of the hemoglobin molecules, renal damage can be avoided, and the substitute does not leave the body so quickly.

Thus far, five products are being tested in people in the U.S. Several of these are made from donated blood that is too old to use. PolyHeme, manufactured by Northfield Laboratories in Evanston, Ill., is a polymerized human hemoglobin that is being evaluated as a replacement for blood during surgery. This compound is prepared by pyridoxylation, which involves reshaping of the hemoglobin molecule to improve its oxygen-carrying capabilities, and then polymerization to increase its size. HemAssist, made by Baxter International in Deerfield, Ill., is also prepared from outdated human blood. This form of cross-linked hemoglobin is being tested during cardiac surgery as well as in people suffering hemorrhagic shock and in trauma patients.

Other products use different approach-

es. Optro, by Somatogen in Boulder, Colo., cross-links human hemoglobin subunits and is produced recombinantly in *Escherichia coli*. And Hemopure, by Biopure in Cambridge, Mass., is made of polymerized hemoglobin from cow's blood. This substitute is being studied for use in trauma, surgery and sickle cell anemia.

Our research, conducted at Enzon in Piscataway, N.J., also centers on bovine hemoglobin. Such hemoglobin is cheap, readily available and, unlike human hemoglobin, does not require the presence of 2,3-DPG to deliver oxygen. By combining bovine hemoglobin with PEG, we have been able to stabilize the molecule, make it larger and increase the time it can spend in the body.

PEG-hemoglobin is currently being evaluated as a way to enhance the radiation treatment of certain solid tumors. Many such tumors have low levels of oxygen at the core, and because radiation therapy requires oxygen to be effective, they resist radiation. Using PEG-hemoglobin, however, some physicians have been able to get oxygen to the tumor. The substitute is also being used for the treatment of stroke and ischemia: because the free hemoglobin is smaller than a red blood cell, it can travel into blocked blood vessels, delivering oxygen to oxygen-starved cells.

Safety in Substitutes

Despite the evident progress, efforts to find a substitute for blood continue to be plagued by lack of success. For every advance, there is a retreat. Because of the volume that would be administered to each patient, researchers must address safety concerns that do not arise for therapeutics administered in smaller amounts. Most drugs are dispensed in milligrams; hemoglobin-based substitutes will be given in amounts as great as 50 to 100 grams. This is because blood substitutes are also used for the purpose of restoring blood volume



COURTESY OF SYNTHETIC BLOOD INTERNATIONAL, INC.

in addition to oxygen-carrying capacity.

Further, the long-term effects of these substitutes are not known. All those being tested have shown some short-term toxicity—including hypertension, renal shutdown and damage, increased heart-beat, and gastrointestinal pain. Because most blood substitutes will be administered in life-threatening situations, researchers will have to prove that short-term benefits outweigh long-term risks—as well as risks arising from chronic use.

Each form of blood substitute also faces its own hurdles. PFC-based compounds must address the problems of retention, toxicity, a short circulating life and the dangers of delivering too much oxygen. Blood substitutes using outdated human blood are faced with the problem of finding enough source material. Genetically engineered, recombinant hemoglobin will have to be produced in staggering amounts—53,000 kilograms annually—to meet just 10 percent of the U.S. demand; such pro-

LIQUID-BREATHING MOUSE is able to survive because of the presence of perfluorocarbons. These compounds can dissolve large quantities of oxygen—thereby allowing this mouse to respire, as Leland Clark showed in the 1960s in this famous photograph. Perfluorocarbons are used in one form of blood substitute.

duction requires massive, costly facilities. Finally, bovine-based substitutes must address the danger of transmission of bovine spongiform encephalopathy and perhaps other not yet identified diseases. Manufacturers can avoid using cows that have been fed the animal by-products blamed for the spread of mad-cow disease, but they must ensure that no other disease-causing agents are present and that there are no adverse immune responses for humans receiving a cow-based product.

Despite these challenges, blood substitutes in clinical trials will be available in the near future. Once approved by the Food and Drug Administration, the products will face the ultimate test: the consumer. What will the consumer be willing to pay for such a product? Or, more important, what will health care providers be willing to pay? Considering the enormous expense of development, these products will undoubtedly cost two to five times more than blood; hospitals currently pay between \$60 and \$85 for one unit of blood, and handling costs often raise that to as much as \$240 per unit. The blood substitute market is estimated to be \$5 billion a year—and that is in the U.S. alone.

Issues of cost aside, however, blood substitutes could significantly improve health care. Forestalling blood shortages and alleviating fears of contamination would be only two of the benefits. Physicians could use substitutes for organ preservation, in the treatment of both anemia and sickle cell anemia and during angioplasty, as well as other procedures. The possibilities are endless. SA

The Authors

MARY L. NUCCI and ABRAHAM ABUCHOWSKI have collaborated on blood substitute research since the late 1980s. Nucci has served as an immunologist at Enzon, a company Abuchowski helped to found. The two recently left Enzon to start New Paradigm Consulting, a medical and scientific consulting group based in New Jersey. In addition to his work on blood substitutes, Abuchowski, who established the Biotechnology Council of New Jersey in 1994, has conducted research on childhood leukemia and has long been devoted to development of drugs for rare conditions.

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Greenland Ice Cores: Frozen in Time

*Ice, frozen in place for tens of thousands of years,
provides scientists with clues to past—and future—climate*

by Richard B. Alley and Michael L. Bender

One of the grand challenges for modern science is to predict climate. Researchers especially wish to learn about large surprises—changes that could help one society flourish or lead another to devastation. Will Europe return to the warmer temperatures of 1,000 years ago, when the Vikings settled Greenland and Britons nurtured vineyards? Or could California suffer extended droughts, lasting centuries, just as the region endured roughly a millennium ago? Recent concerns about global warming and the effects of man-made greenhouse gases have only heightened the need to understand the basic natural processes that cause the climate to change.

To gain this fundamental knowledge, climatologists have turned to the past. Drilling deep below the surface of ice sheets and glaciers in Greenland, Antarctica and elsewhere, scientists have obtained water frozen for tens of thousands of years. Trapped in the ice are trace chemical impurities containing precious information about ancient climate.

Recent work by European and U.S. teams, including us, studying cores of ice from deep drillings in Greenland has shown that large, rapid changes in climate, typically lasting a few hundred to several thousand years, punctuated the longer cycles between glacial (cold) and interglacial (warm) periods. Modern cultures have not experienced such dramatic swings. What caused them? Did they occur simultaneously in the high

CENTRAL GREENLAND, where snow has accumulated for more than 100,000 years, offers researchers the opportunity to probe ancient climate change by drilling into the glacier below.

latitudes of the Northern and Southern hemispheres? How were the tropics affected? The answers to these questions could provide a window to the future. Although current concerns about climate change focus on the influence of human activities, ancient shifts may have been fated by the heavens.

Celestial Effects

During the 1920s and 1930s, Milutin Milankovitch, a Serbian astronomer, studied how the gravitational pull from other planets causes subtle changes in the orbit of the earth. These alterations result in different distributions and intensities of sunlight, which then lead to dramatic variations in climate over tens of thousands to hundreds of thousands of years. Milankovitch investigated three orbital variables: the

tilt of the spin axis; the precession of the tilt (a motion similar to the wobbling of a spinning top); and the eccentricity in the orbit around the sun (that is, whether the orbit is almost circular or stretched out into a more elongated ellipse). Changes in these three parameters cause slow but distinct oscillations in climate with periods of about 40,000 years (governed by tilt),

20,000 years (precession) and 100,000 or more years (eccentricity) [see “What Drives Glacial Cycles?” by Wallace S. Broecker and George H. Denton; SCIENTIFIC AMERICAN, January 1990].

Many contemporaries of Milankovitch denounced his astronomical theory of climate change, which remained largely unproved up to his death in 1958. Subsequently, however, scientists studying sediments deposited on the bottom of the ocean made some landmark discoveries. They found that the past few million years have been characterized by a repeated series of temperature changes during which great glaciers advanced and retreated over vast areas, all the time marching to the beat predicted by Milankovitch. For at least the past half a million years, the basic climate cycle—the period from one glacial or interglacial extreme to the next—has been about 100,000 years, with shorter-term oscillations of roughly 20,000 and 40,000 years.

More recently, researchers have sought to study ancient climate in even finer detail. To that end, investigators have directed some of their attention away



RICHARD B. ALLEY

from ocean sediments and have examined cores extracted from depths down to three kilometers (about two miles) below the surface of the great ice caps of Greenland and Antarctica, among other areas [see "The Antarctic Ice," by Uwe Radok; *SCIENTIFIC AMERICAN*, August 1985]. But scientists could not have drilled just anywhere in these frozen wastelands; they had to find "good" glacial deposits, where snow has accumulated over tens of thousands of years. As the snow piles up in such places, it compresses under its own weight and eventually forms ice, preserving in the process a wealth of information about the climate.

Age-Old Question

The crucial prerequisite in the study of ice cores is the accurate determination of the age of the specimens. Without these data, scientists could not build an overall chronology in which to place their other measurements. Fortunately, investigators can often determine the age of the ice by simply counting off the number of years.

In places such as central Greenland, where it snows frequently, the ice forms in annual layers that can be analyzed in much the same way that yearly growth rings can be used to determine the age of a tree. The layering in glacial ice is often noticeable with the naked eye because crystals from summer snow are larger than those of winter snow. Climatologists can also detect the annual layers by measuring the acidity of the ice, which is generally higher for summer snow for reasons that remain somewhat obscure. And researchers can use a laser to determine the concentration of dust particles in an ice specimen. The number of dust particles typically rises in the spring because of the greater strength of the wind in that season.

Using these and other indicators, one of the authors (Alley) worked with his colleagues on the U.S. ice-coring project in Greenland, headed by Paul A. Mayewski of the University of New Hampshire, to obtain a chronology that compares well with several independent measures. For example, an analysis of the composition of ash found in certain layers of ice enabled the team to identify the volcanoes involved and the corresponding historical dates of the eruptions. Such corroborative testing indicates that the counting of annual strata introduces virtually no errors for Green-

STEVE STARR/SABA

Slicing through Time

Scientists make many different kinds of observations in their efforts to decipher the record of climate held in ice cores (such as the cut example at the left). Some key methods of analysis appear below.



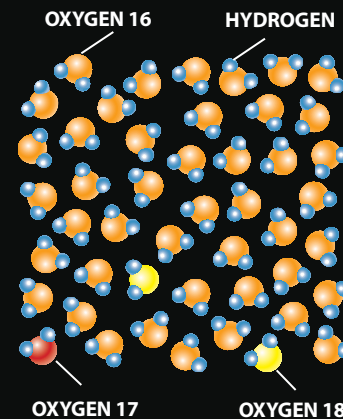
RICHARD B. ALLEY

ANNUAL LAYERS, often visible with the naked eye, are usually horizontal, but slow movement of the glacier sometimes distorts them into Z-shaped folds.



RICHARD B. ALLEY

AIR BUBBLES become trapped in the snow as it compresses into ice. These samples of the ancient atmosphere reveal how concentrations of greenhouse gases such as carbon dioxide and methane have changed.



JENNIFER C. CHRISTENSEN

OXYGEN ATOMS in the ice can vary in composition. The relative abundance of the different types reflects the temperature at the time of precipitation.

MEASUREMENTS of ancient temperature (a) and atmospheric methane (b) from the Greenland ice cores have corroborated earlier findings about climate at Vostok, Antarctica (c), and for the total volume of ice around the world, as determined from the analyses of deep-sea sediments (d). In particular, the different research shows a warm period approximately every 20,000 years. A more gradual trend of cooling until 20,000 years ago and the rapid warming between 20,000 and 10,000 years ago follow a longer, approximately 100,000-year cycle.

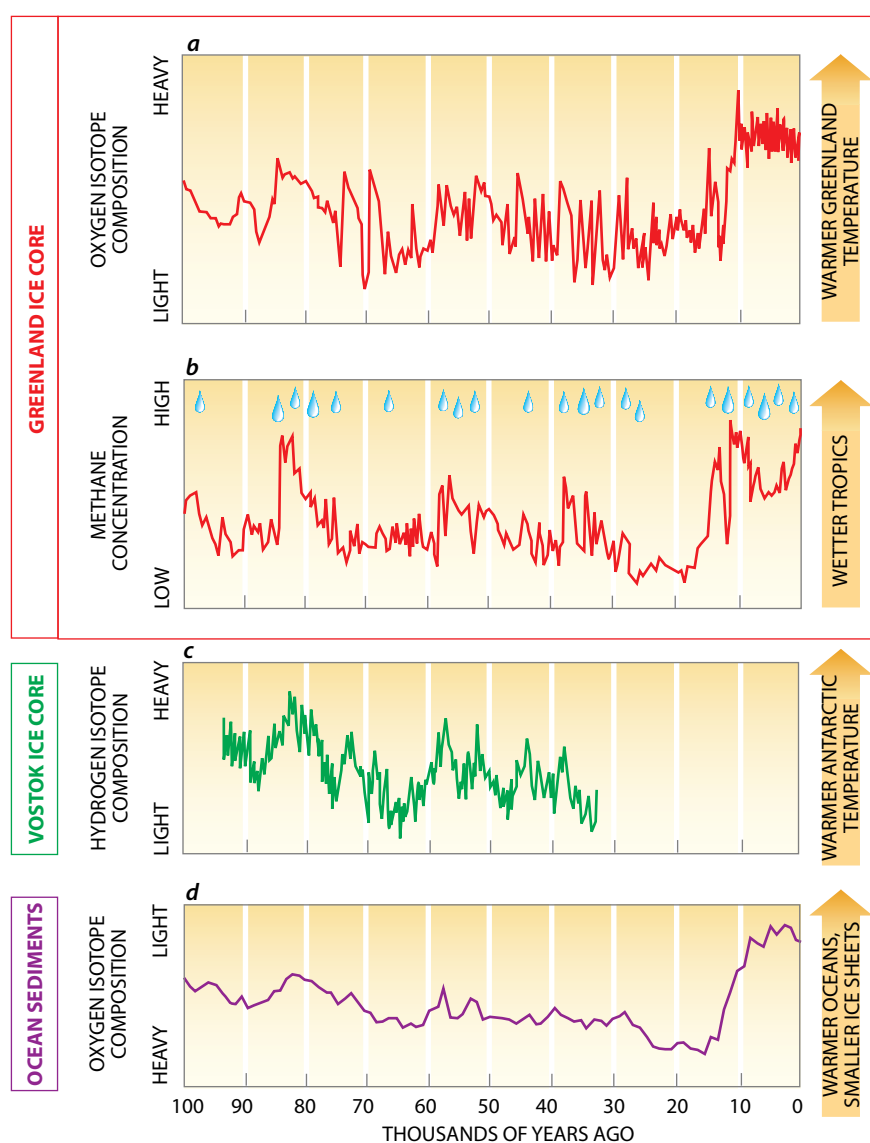
land ice that is several centuries old. For the most recent 11,500 years, the so-called Holocene warm period, layer counting is correct to within 1 percent. Although the accuracy is somewhat poorer in older ice from colder times, it appears to be as good as that of other dating techniques to at least 50,000 years ago. Arguably annual layers remain visible past 100,000 years, but they often appear distorted.

Why are these deep layers so disrupted? Although nominally solid, glaciers and ice sheets spread and thin under the influence of gravity, similar to the motion of pancake batter poured on a griddle. As the movement continues over tens of thousands of years, the bottom layers of ice become extremely drawn out (sometimes disappearing altogether) and crumple easily as the glacier oozes over the ground below.

The resulting deformations make it impossible to count annual layers continuously below a certain depth. For example, the cores the U.S. team obtained in Greenland contained layers that, from top to bottom, went from being horizontal, to having small wiggles, to showing Z-shaped folds, to becoming slanted at angles up to 20 degrees in ice older than about 110,000 years. Cores taken nearby in a parallel effort by European researchers revealed a similarly complex (yet different) pattern in ice older than 110,000 years.

This dissimilarity helped to solve a puzzle. Ice initially believed to be from the previous interglacial period—the Eemian, which ended about 120,000 years ago—indicated severe climate changes with rapid and repeated swings. The result was both surprising and alarming: climatologists had viewed both the present and past warm interglacial times as stable and free of such wild shifts.

Scientists thus began a series of care-



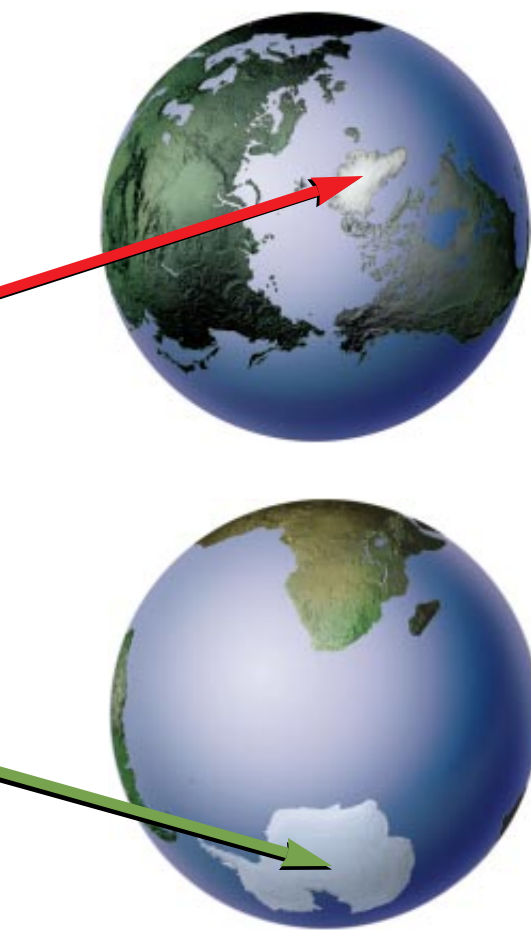
ful examinations that have since shown that flow of the ice disrupted the older layers in both the European and U.S. cores. A clue was that the two sets of climatic records were virtually identical during the most recent 110,000 years but that they could not be positively matched for older times. Apparently, these disturbances occurred farther above the bed than originally had been expected. Paleoclimatologists are now beginning to understand such effects and are developing additional techniques, such as computer simulations, to recognize them.

To obtain a reliable Eemian record, the European team has commenced another deep-drilling project in Greenland, about 340 kilometers northwest of the two earlier drill sites. Layers older than 110,000 years at the new location are thought to be higher above the bedrock

than those at the previous bore positions. Thus, distortions from the flow of ice are less likely to be acute.

Ice-Core Secrets

If the Europeans succeed, scientists will gain important insight into how the climate operated, in large part from their estimates of ancient temperatures. The primary thermometer used for this purpose takes advantage of the fact that water comes in “light” and “heavy” flavors, or isotopes. Light isotopes have only ordinary hydrogen and oxygen; heavy ones contain either hydrogen with an added neutron (deuterium) or oxygen with one or two extra neutrons (oxygen 17 or oxygen 18). The cooling of an air mass causes precipitation, which removes more of the heavy water (because of its lower vapor pressure) from the



moisture-laden atmosphere. Consequently, snowfall at an inland site during colder times tends to contain “lighter” water, the heavy isotopes having already been squeezed out of the air as it traveled over the ocean and the flanks of the ice sheet before reaching the site.

A second thermometer for ancient climate comes from the current temperature of the ice sheet. Just as a frozen roast placed in a hot oven will tend to maintain the temperature of its former environment by remaining frozen in the center even as its outside begins to warm, the ice sheet is actually colder a kilometer or two (or about a mile) down than at the surface. In essence, the older ice “remembers” the extreme temperatures of the last ice age. Taken together, the two thermometers show that the severest periods of the last ice age were indeed quite frigid—on average Greenland was colder by more than 20 degrees Celsius (36 degrees Fahrenheit) than it is currently.

In addition to records of temperature, ice cores contain a history of precipitation. Scientists have, for example, used the thickness of an annual layer (after

correction for any distortions caused by the flow of ice) to gauge the amount of snow that year. This analysis revealed that the coldest periods in central Greenland had four to five times less precipitation than today.

Further clues to ancient climate are supplied by windblown materials trapped in the ice. Coarser dust particles suggest winds of greater strength. Researchers can, in fact, track past patterns of atmospheric circulation by using the composition of the dust to determine its source, just as the analysis of ash enables the identification of the volcanic eruption involved. Other trace materials found in the ice cores include chemicals from marine algae and radioactive isotopes produced in the air by cosmic rays.

A decreased concentration of these substances indicates either a smaller supply or an increased amount of snowfall, which dilutes these materials. Because the annual layering in cores from central Greenland allows scientists to determine the rate at which snow accumulated, they have been able to separate the two effects. After doing so, they uncovered up to 100-fold changes over time for some windblown imports such as calcium, indicating that much stronger winds and perhaps larger deserts existed during cold intervals.

The ice is also an excellent storehouse for samples of ancient air. In freshly fallen snow, gas molecules circulate easily through pores between the ice crystals. The massive weight of snow that piles up on a polar ice sheet, however, presses down on the deeper layers, causing the pores to become smaller and smaller until, between a depth of about 40 and 120 meters, the compression is great enough that air becomes imprisoned as individual bubbles in the ice.

Analyses of these tiny air samples by one of us (Bender) and others studying ice from Greenland and Antarctica reveal how concentrations of atmospheric gases have changed over time. In particular, scientists have determined how various heat-trapping greenhouse gases have varied naturally. From glacial to interglacial periods, for example, the concentrations of carbon dioxide and methane surged by about 50 and 75 percent, respectively. This information has helped put the recent additional increases caused by human activities—30 percent for carbon dioxide and 160 percent for methane—into perspective.

Studies of trapped gas have an ancil-

lary benefit. Because the global atmosphere mixes rapidly, its makeup everywhere is almost the same. Thus, researchers can safely assume that changes in the atmospheric composition occurred simultaneously in Greenland and Antarctica, allowing them to use gas measurements to correlate ice cores taken from opposite sides of the world.

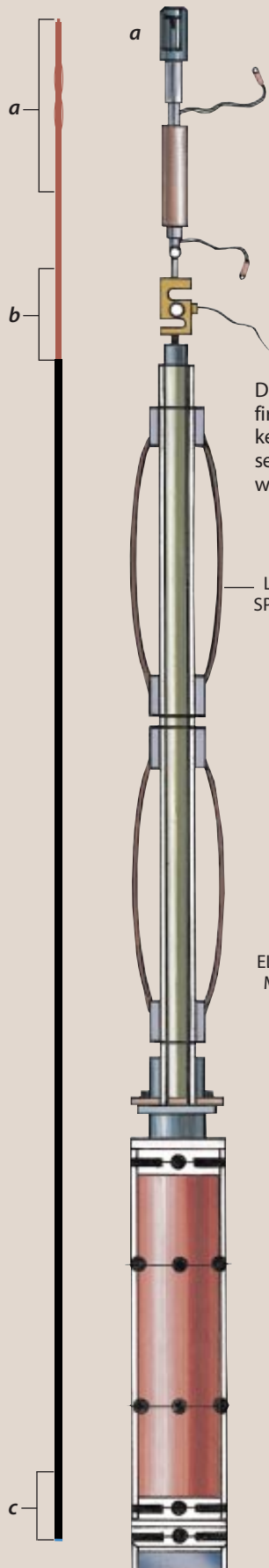
Flickering Climates

Examination of the Greenland ice cores has bolstered the results of previous investigations of Antarctic ice cores and deep-sea sediments. Combined, the different studies provide solid support for Milankovitch’s astronomical theory of climate change. For example, the different records show warm temperatures at about 103,000, 82,000, 60,000, 35,000 and 10,000 years ago, which roughly reflect Milankovitch’s 20,000-year precession cycle.

But perhaps the most striking features of the Greenland ice-core results are “interstadial events”: intervals lasting a few hundred to a few thousand years during which Greenland warmed rapidly, then cooled at first slowly, then quickly. The Greenland ice cores clearly show that between 100,000 and 20,000 years ago, approximately two dozen interstadial events occurred—all unpredicted by Milankovitch theory.

Interestingly, the Greenland ice cores demonstrate that the methane concentration of the atmosphere increased during each interstadial event. Methane is produced by bacteria in environments where oxygen is scarce—for example, in tropical swamps and bogs. The higher methane levels in the ice indicate that the tropical wetlands must have expanded during interstadial times, evidently because of increased rainfall.

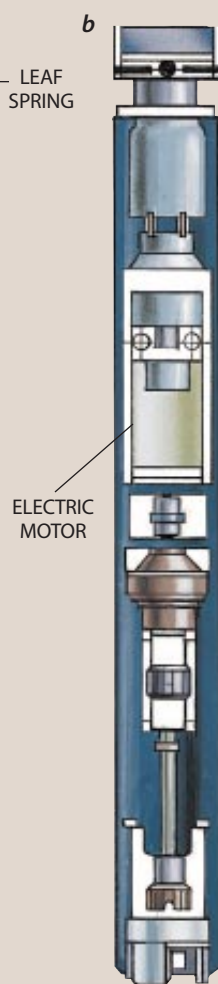
An intriguing characteristic of interstadial events is their abruptness. Changes of perhaps five to 10 degrees C (nine to 18 degrees F) or more, twofold in snow accumulation and up to 10-fold in dustiness occurred over mere decades, sometimes even during as little as a few years. This dramatic behavior was most prominent during times of intermediate temperatures over the past 100,000 years; the coldest part of the ice age and the modern period of warmth appear stabler in comparison. Right before and after the large interstadial jumps, the climate at times took smaller hops back and forth between warm and cold—a behavior that scientists have dubbed



Tools of the Trade

The drill, essentially a hollow barrel with sharpened cutters at the tip, is lowered into the borehole on a cable from an indoor platform (right). To prevent the hole from collapsing on itself, technicians inject a fluid such as butyl acetate (a pineapple-smelling food additive) to equalize pressure with respect to the surrounding ice.

Detail *a* shows leaf springs that firmly grip the adjacent ice to keep the upper part of the assembly from twisting or spinning while the lower part is drilling.



Detail *b* shows the electric motor attached to the tube. This motor spins the cutters against the ice, making chips that are pumped up the outside of the barrel. Such drilling leaves a cylinder, or core, of solid ice inside.



Detail *c* shows the sharpened, pivoting metal "core dogs," which are designed to ride lightly down the outside of the core during drilling. When technicians raise the barrel, the dogs, which are slanted slightly upward, dig into the bottom of the core, freeing it from the surrounding ice. The dogs also hold the core inside the barrel while the entire assembly is winched up the hole.



MARK TWICKLER/University of New Hampshire

flickering. So, in addition to the interstadial shifts, the climate apparently bounces repeatedly between a warm and a cold mode—all when Milankovitch would have predicted gradual transitions.

Beyond Milankovitch

To explain such seemingly erratic behavior, scientists have begun to investigate other factors in addition to the earth's orbit. Using sophisticated computer models, researchers have sought to understand "teleconnections," by which changes in the climate of one geographic region trigger variations elsewhere. For example, recent investigations indicate that warming in high latitudes could alter the circulation of the ocean or atmosphere in ways that would also heat the tropics. Such warming at low latitudes would enable water to evaporate more quickly there. That increase in the amount of water vapor (a greenhouse gas) would, in turn, trap more heat near the surface of the earth.

Similarly, during glacial times the vast continental ice sheets and the enormous expanses of frozen ocean around them reflected much sunlight back to space. In warm times, melting of the ice sheets allowed more of the sunlight to be absorbed. And the higher concentration of

carbon dioxide, as well as other greenhouse gases such as methane and water vapor, led to more heat retention.

Because of such interactions, climatologists reasoned that different regions of the planet would warm or cool together. It came as a surprise, then, when Thomas F. Stocker of the University of Bern and Thomas J. Crowley of Texas A&M University independently predicted in 1992 that for rapid climatic events, Greenland and Antarctica would change oppositely.

Studying the effects of ocean currents, Stocker and Crowley noted that today's tepid, salty waters flow in the Gulf Stream from the equator toward the Arctic, where they release heat to the atmosphere, giving northern Europe its relatively equable climate. After cooling, the salty waters become dense and sink to the deep ocean, where they then flow southward as part of a great "conveyor belt." During the harsh, stadial times of the ice ages, the conveyor was off or weakened, and the resulting slower flow of equatorial waters to the Arctic left Greenland and northern Europe particularly frigid. During interstadial periods, the conveyor strengthened.

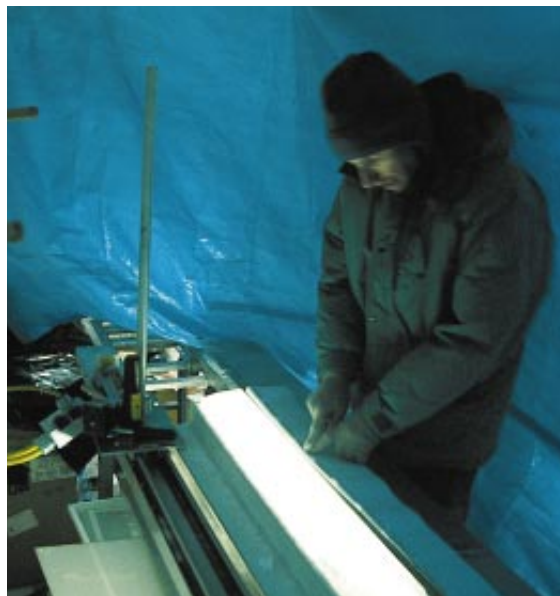
Stocker and Crowley examined how this oceanic circulation affects the climate of the Southern Hemisphere. Their special insight was to show that the conveyor cools the south at the same time it warms the north, and vice versa, because of two effects. First, the flow of cold, deep waters to the Southern Hemisphere causes a return current of shallower, warmer waters to the north, which brings additional heat there while robbing it from the south. Second, slowing of the conveyor causes more warm waters to reach the surface of the sea around Antarctica, where they release

heat that warms the air in the far south.

Support for this theory of out-of-synch climate change came in the mid-1990s, when scientists studying fossil foraminifera (microscopic seashells) found that the Antarctic Ocean was warm when the conveyor was not operating. Furthermore, in light of the predictions of Stocker and Crowley, Wallace S. Broecker of Columbia University re-examined the climate records during the last deglaciation, between 20,000 and 10,000 years ago. He showed that warming stalled in Antarctica during times of rapid temperature increases in Greenland, and vice versa.

Bender and several other colleagues have shown that all the major stadial and interstadial events recorded in the Greenland ice cores are also present in Antarctica, although climate changes in the south were not as large or abrupt. Uncertainties in dating the cores precisely have made it difficult to determine whether cooling in Greenland caused warming in Antarctica for all these events. Laboratories in Grenoble, Bern and elsewhere are now in the process of extending exact correlations back to the middle of the last ice age.

This interest in the relative timing of climate change in polar regions is one of the factors spurring new efforts to extract deep ice cores from Antarctica. Teams from the U.S., Japan, Europe and



MARK TWICKLER University of New Hampshire

EXAMINATION OF ICE CORES by various teams from the U.S., Japan, Europe and Australia is currently taking place in Antarctica and Greenland. One goal of these studies is to determine how the climate in the south and north are related.

Australia all have deep-drilling projects under way. One goal is to obtain cores containing climate records for the past 110,000 years (or earlier, if possible) that can be precisely correlated with the measurements from Greenland.

These research programs, in addition to the ongoing European effort in Greenland, will help answer fundamental questions about the climate during oscillations between glacial and interglacial periods. Only by obtaining this fuller understanding of the past can scientists begin to predict future climate, including the severity of greenhouse warming in the near term and, further off, the timing of any possible return to an ice age.

SA

The Authors

RICHARD B. ALLEY and MICHAEL L. BENDER were members of the U.S. team that extracted and analyzed ice cores from central Greenland in the early 1990s. Both men are currently involved in the U.S. project drilling for ice cores in West Antarctica. Alley is professor of geosciences at Pennsylvania State University and an associate at the Earth System Science Center there. He received his Ph.D. in geology from the University of Wisconsin. His recent research includes studying how glaciers and ice sheets record climate change, how their flow affects sea level, and how they erode and deposit sediments. Bender is professor in the department of geosciences at Princeton University. He did his graduate studies at the Lamont-Doherty Earth Observatory of Columbia University. He was with the Graduate School of Oceanography at the University of Rhode Island for 25 years. His current research includes analyzing oxygen and its isotopes as a means to learn about ancient climates.

Further Reading

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Everyday Exposure to Toxic Pollutants

Environmental regulations have improved the quality of outdoor air. But problems that persist indoors have received too little attention

by Wayne R. Ott and John W. Roberts

Imagine that a killer is on the loose, one who shoots his victims and flees. Police investigators would undoubtedly respond by visiting each crime scene and meticulously searching for clues. They would photograph the body, take fingerprints and question witnesses. An autopsy would recover the bullet for tests. The authorities could then use this information to establish exactly who was responsible.

But suppose the police took a different approach. What if they decided to start by examining all the guns that had recently been fired? Surely one of these weapons, they could argue, was involved. And they would be correct. They might even succeed in identifying the

murderer—but not until after they had expended tremendous energy looking over a great number of firearms carried by law officers, soldiers and duck hunters. In a world of limited resources, they would probably run out of time and money before they came close to finding the culprit.

Surprisingly, officials charged with guarding the general population from toxic pollutants rely almost universally on the second strategy. Most environmental laws in the U.S. seek to control only the release of potentially dangerous wastes into the air and water, not

the amount of contact people actually have with those pollutants. This focus on emissions rather than exposure essentially disregards the reality that toxic substances produce health problems only if they reach the body.

That oversight is, to some extent, understandable: for far too long, little information existed about the extent to which most citizens were exposed to the pollutants that the nation controls. Regulators seldom knew with any certainty the number of people affected by a given pollutant, the severity of exposure or the specific sources of the worrisome chemical. The result was that officials often focused on limiting pollution from the most apparent sources, such

CARBON MONOXIDE LEVEL
(PARTS PER MILLION)

DAILY ROUTINES expose many people to potentially harmful substances, including particles smaller than 2.5 microns in size (yellow bars), toxic volatile organic compounds (red bars) and carbon monoxide gas (gray line). The Environmental Protection Agency has set formal standards for outdoor exposure to such particles (daily average limit shown) and to carbon monoxide (eight-hour average limit shown), but acceptable limits for exposure to various toxic volatile organic compounds have been more difficult to assign. Estimates (for particles and the predominant volatile organic compound) or direct measurements (for carbon monoxide) in various "microenvironments" in one man's day illustrate how much one's exposure can fluctuate, with the highest levels of exposure typically arising during indoor activities.

RESPIRABLE PARTICLES
(R.P.)



MICROGRAMS
PER CUBIC
METER

TOXIC VOLATILE
ORGANIC COMPOUNDS (V.O.C.)



MICROGRAMS
PER CUBIC
METER

OUTDOORS IN AN URBAN SETTING

V.O.C. [] ANY OF SEVERAL
R.P. [] DIFFERENT COMPOUNDS



as automobiles and factories, while failing to address many other important but less obvious ones.

Fortunately, the science of assessing people's exposure to toxic substances has matured. In particular, scientists have developed highly sensitive analytical instruments and portable monitoring devices. Researchers have exploited this equipment in large-scale field studies, designed to gauge just where and how people are exposed to potentially dangerous chemicals.

Getting Personal

In 1980 one of us (Ott), along with Lance A. Wallace of the U.S. Environmental Protection Agency, launched the first serious efforts to assess everyday exposure of the general population to toxic substances. That program, carried out primarily by the Research Triangle Institute in North Carolina and other contract research organizations, later expanded to include some two dozen studies in 14 U.S. states. Using the same methods, researchers sponsored by private industry conducted similar studies in a 15th state (Alaska) and in one Canadian province. Most of these investigations employed monitoring instruments that were small and light enough for people to carry as they went about their normal activities. These devices showed which pollutants existed close by and in what concentration. In some cases, the researchers also made measurements of the food and water con-

sumed. In certain instances, they determined the blood levels of various pollutants from breath samples.

So far these studies of "total human exposure" have examined the prevalence of volatile organic compounds, carbon monoxide, pesticides or dangerous particles in the daily lives of more than 3,000 subjects, a carefully chosen slice of the population meant to be representative of most North Americans living in urban or suburban areas. Chemical analyses of the samples were detailed enough to identify the specific chemicals to which the participants were routinely exposed. For instance, the investigations of volatile organic compounds typically tested for some 30 different chemicals, including many known to cause cancer in people or animals.

It is difficult to know whether the contacts most people have with these substances pose an especially large health risk, because the capacity for low levels of each compound to cause sickness is exceedingly hard to estimate. Still, these studies produced results that were disturbing: most citizens were very likely to have the greatest contact with potentially toxic pollutants not outside but inside the places they usually consider to be essentially unpolluted, such as homes, offices and automobiles. The exposure arising from the sources normally targeted by environmental laws—Superfund sites, factories, local industry—was negligible in comparison.

Even in the New Jersey cities of Bayonne and Elizabeth, both of which have

an abundance of chemical processing plants, the levels of 11 volatile organic compounds proved much higher indoors than out. (Concentrations of the other volatile compounds tested were found to be insignificant in both settings.) The chief sources appeared to be ordinary consumer products, such as air fresheners and cleaning compounds, and various building materials.

Could everyday items with which people happily share their homes truly be more of a threat to their health than industrial pollution, even for people whose communities are surrounded by factories? In short, the answer is yes. For example, benzene—a chemical known to cause leukemia in workers continually exposed to high concentrations—is present in gasoline and in some household products. It is also one of about 4,000 chemicals found in tobacco smoke, so living with a smoker raises one's exposure to benzene enormously.

In 1985 Wallace combined all the existing information about how several hundred people located in five different states were exposed to this compound. He found that the average concentration of benzene they inhaled was nearly three times higher than typical outdoor levels. He calculated that some 45 percent of the total exposure of the U.S. population to benzene comes from smoking (or breathing smoke exhaled by others), 36 percent from inhaling gasoline fumes or from using various common products (such as glues), and 16 percent from other home sources (such

EPA
LIMIT
—9

—6

—3

—0

PHOTOGRAPHY BY BERND ALIERS; JENNIFER C. CHRISTIANSEN (charts)

STEAMY BATHROOM

V.O.C. CHLOROFORM
R.P.

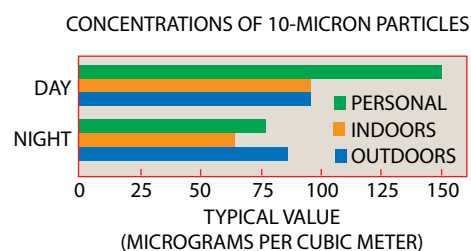
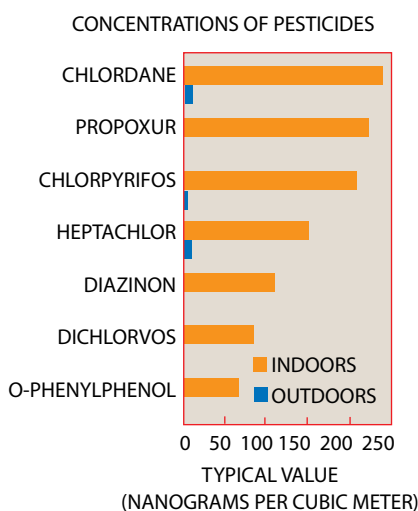
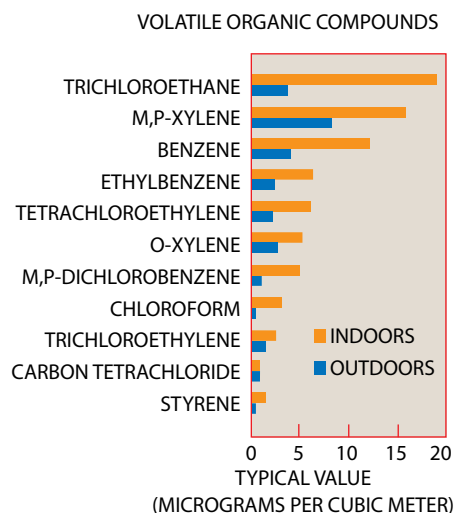
DRY-CLEANED CLOTHES IN CLOSET

V.O.C. PERCHLOROETHYLENE
OR TRICHLOROETHANE
R.P.

ENCLOSED PARKING GARAGE

V.O.C. BENZENE AND SEVERAL
OTHER COMPOUNDS
R.P.





EXPOSURE STUDIES reveal that people come into contact with toxic volatile organic compounds and pesticides more indoors than outside. Most people's exposure to breathable particles during the day is higher than ambient levels in the air (either indoors or outside), because moving about stirs up a "personal cloud."

as paints and gasoline stored in basements or attached garages). He attributed only 3 percent of the average person's exposure to industrial pollution.

In contrast, government regulators usually consider only the gross amount of benzene released into the general environment, for which the largest share comes from automobiles (82 percent), followed by industry (14 percent) and domestic sources (3 percent). Cigarettes contribute only 0.1 percent of the total. Wallace's work aptly demonstrated that cutting all industrial releases of benzene would reduce health risks by only a tiny fraction. Yet even a modest reduction in cigarette smoking—the smallest source of benzene in the atmosphere—would significantly reduce the likelihood of benzene causing disease.

Many other volatile organic compounds that are quite toxic at high con-

centrations are also more prevalent indoors than out. For example, the chemical tetrachloroethylene (also known as perchloroethylene or "perc"), which has been shown to cause cancer in laboratory animals, is used to dry-clean clothes. Thus, the greatest exposure occurs when people live in a building with dry-cleaning facilities, wear recently dry-cleaned clothes or store such chemically laden garments in their closets. Moth-repellent cakes or crystals, toilet disinfectants, and deodorizers are the major source of exposure to paradichlorobenzene, which also causes cancer in animals. Studies have consistently indicated that almost all exposure to paradichlorobenzene comes from sources inside homes, not from industrial emissions or hazardous-waste sites.

Although assessments of the risks to health are somewhat uncertain, it is clear

that less contact with toxic volatile organic compounds is better than more. Most people can limit potentially harmful exposure by avoiding products that contain such pollutants. But other worrisome vapors are difficult to avoid.

For example, the major sources of exposure to chloroform—a gas that provokes concern because it can cause cancer in animals subjected to high concentrations—are showers, boiling water and clothes washers. It forms from the chlorine used to treat water supplies. Because piped water is something that people simply cannot do without, the only way to minimize household exposure to chloroform is to drink bottled water (or tap water that is run through a good-quality charcoal filter) and to improve ventilation in the bathroom and laundry.

Better airflow can also help lower ex-

PHOTOCOPIER WITH DRY TONER

V.O.C. [Red bar] FORMALDEHYDE
R.P. [Yellow bar] STYRENE AND OTHERS



ENCLOSED SPACE WITH SMOKERS

V.O.C. [Red bar] BENZENE AND MANY
R.P. [Yellow bar] OTHER COMPOUNDS



CARPETED HOME

V.O.C. [Red bar] PESTICIDES OR
R.P. [Yellow bar] OTHER COMPOUNDS



SOURCES OF BENZENE EMISSIONS



SOURCES OF BENZENE EXPOSURE



BENZENE, a volatile organic compound that causes cancer in humans, is quite common. But the sources that produce the greatest quantity of emissions (automobile exhaust and industry)

contribute only modestly to the exposure of the general populace, which faces a considerably greater threat from the benzene released by cigarettes, gasoline vapors and consumer products.

posure to carbon monoxide, a product of incomplete combustion that robs the blood of oxygen and can be particularly harmful to people with heart ailments when inhaled at levels often found indoors. Although studies conducted in the early 1980s in Denver and Washington, D.C., confirmed that carbon monoxide levels rose precipitously when people were in or near motor vehicles, other research has demonstrated that indoor appliances, such as poorly operated gas stoves, grills and furnaces, can also cause extremely unhealthy conditions—even death. Fortunately, outdoor levels of carbon monoxide have steadily declined in the U.S. in concert with the reductions in automobile emissions, as required by federal regulations. Yet further progress will be more difficult, because on the whole the U.S. population now receives greater exposure to carbon monoxide indoors than out.

Another environmental concern that appears more severe indoors is the danger from fine particles in the air. In one study, researchers used miniaturized monitors to collect minute particles in and around 178 homes in Riverside,

Calif. Respondents carried devices that gathered particles 10 microns or less in diameter, ones small enough to penetrate into the lungs.

Curiously, exposures during the day were about 60 percent greater than expected from the particulate levels measured in samples of air concurrently taken indoors and outside. The higher exposures arose, at least in part, because people do not simply float through the air; rather they tend to stir up “personal clouds” of particle-laden dust from their surroundings as they move about. These investigators showed that most of these fine particles form through combustion—such as smoking, cooking, burning candles or firewood. Finding such pollutants indoors is troubling, because recent epidemiological studies have associated elevated concentrations of fine particles outdoors with premature death.

Even more disturbing were the results from two studies of indoor air contaminants conducted during the late 1980s in Jacksonville, Fla., and Springfield, Mass. In those places, investigators found that indoor air contained at least

five (but typically 10 or more) times higher concentrations of pesticides than outside air—and those residues included insecticides approved only for outdoor use. Evidently, potent chemicals targeted against termites in the foundations of these houses had found their way indoors. Such poisons can be tracked in on people’s shoes, or they may seep through the soil as a gas into homes. Chlordane (which was taken out of products sold for home use in 1988) and some other pesticides contaminating the air indoors caused a greater share of exposure than the amounts found on food.

In addition, people sometimes apply inappropriate pesticides directly to indoor surfaces, unaware that they are causing their own high exposures. And even the most enlightened homeowners are often ignorant of past applications of dangerous chemicals. Pesticides that break down within days outdoors may last for years in carpets, where they are protected from the degradation caused by sunlight and bacteria. This persistence is well demonstrated by measurements of the pesticide DDT (dichlorodiphenyltrichloroethane), which was outlawed

KITCHEN FUMES



ANY OF SEVERAL COMPOUNDS

COMMON HOUSEHOLD PRODUCTS



PARADICHLOROBENZENE AND SOLVENTS

OUTDOORS IN THE SUBURBS



ANY OF SEVERAL COMPOUNDS



in the U.S. in 1972 because of its toxicity. Despite that long-standing prohibition, Jonathan D. Buckley of the University of Southern California and David E. Camann of the Southwest Research Institute found that 90 of the 362 Midwestern homes they examined in 1992 and 1993 had DDT in the carpets.

Indeed, that study showed that the contaminants lurking in people's carpets are not restricted to pesticides. In more than half of the households Buckley and Camann surveyed, the concentrations of seven toxic organic chemicals called polycyclic aromatic hydrocarbons (compounds produced by incomplete combustion, which cause cancer in animals and are thought to induce cancer in humans) were above the levels that would trigger a formal risk assessment for residential soil at a Superfund site.

Small People, Big Problems

The pesticides and volatile organic compounds found indoors cause perhaps 3,000 cases of cancer a year in the U.S., making these substances just as threatening to nonsmokers as radon (a natural radioactive gas that enters many homes through the foundation) or secondhand tobacco smoke. And toxic house dust can be a particular menace to small children, who play on floors, crawl on carpets and regularly place their hands in their mouths. Infants are particularly susceptible: their rapidly developing organs are more prone to damage, they have a small fraction of the body weight of an adult and may

ingest five times more dust—100 milligrams a day on the average.

Before 1990, when the EPA and U.S. Department of Housing and Urban Development established standard methods for sampling dust on carpets, upholstery and other surfaces, it was difficult to quantify the risk to children. Since then, however, improved techniques have allowed scientists to make more concrete statements about the degree of exposure. For example, we can now estimate that each day the average urban infant will ingest 110 nanograms of benzo(a)pyrene, the most toxic polycyclic aromatic hydrocarbon. Although it is hard to say definitively how much this intake might raise a child's chance of acquiring cancer at some point, the amount is sobering: it is equivalent to what the child would get from smoking three cigarettes.

The research also points out that, for small children, house dust is a major source of exposure to cadmium, lead and other heavy metals, as well as polychlorinated biphenyls and other persistent organic pollutants. Carpets are most troublesome because they act as deep reservoirs for these toxic compounds (as well as for dangerous bacteria and asthma-inducing allergens, such as animal dander, dust mites and mold) even if the rugs are vacuumed regularly in the normal manner. Plush and shag carpets are more of a problem than flat ones; floors covered with wood, tile or linoleum, being the easiest to clean, are best.

One of us (Roberts), along with several colleagues, has shown that people

can prevent the accumulation of dangerous amounts of dust by using a vacuum equipped to sense when no more particles can be extracted. Other of our studies have indicated that simple preventive acts can help considerably. For example, wiping one's feet on a commercial-grade doormat appears to reduce the amount of lead in a typical carpet by a factor of six. Because lead exposure is thought to affect more than 900,000 children in the U.S., the use of good doormats would translate into a significant boost to public health.

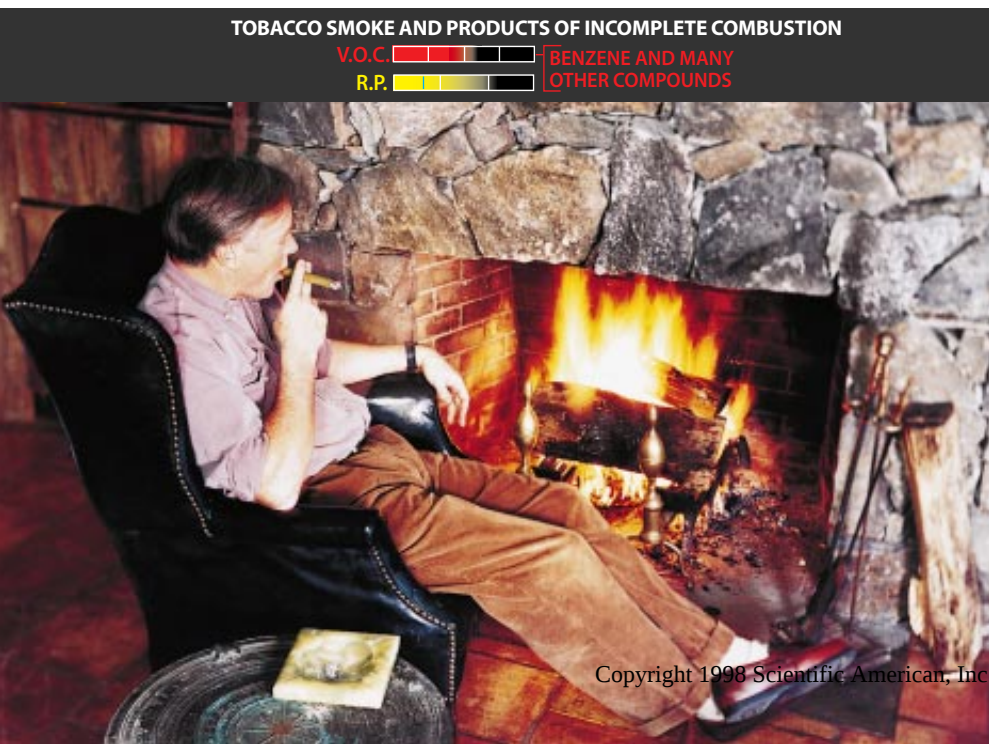
Removing one's shoes before entering is even more effective than just wiping one's feet in lowering indoor levels of the toxic pollutants that contaminate the environs of most homes (such as lead from peeling paint and pesticides from soils around the foundation). By taking such precautions to avoid tracking in dust and using an effective vacuum cleaner—one equipped with a rotating brush and, preferably, a dust sensor—people can reduce the amount of lead and many other toxic substances in their carpets to about a tenth (or, in some cases, to a hundredth) of the level that would otherwise persist.

Unfortunately, most people are unaware of the ubiquity of indoor pollution or of how to reduce it. One innovative initiative by the American Lung Association in Seattle aims to remedy that problem by training volunteers (dubbed "master home environmentalists") to visit dwellings and help residents limit domestic environmental threats.

Trouble with the Law

The many findings now available from multiple studies of people's everyday exposure all point to a single conclusion—that the same air pollutants covered by environmental laws outdoors are usually found at much higher levels in the average American residence. This situation has come about, at least in part, because the U.S. has made remarkable progress in improving the quality of outdoor air over the past three decades by controlling automobile and industrial emissions. Of the hundreds of air pollutants covered under existing U.S. laws, only ozone and sulfur dioxide remain more prevalent outdoors.

So it is peculiar that more attention has not yet shifted toward indoor pollution, the main sources of which are not difficult to identify. In fact, they are right under people's noses—moth repel-



SURFACE SAMPLER draws in particle-laden air in the same manner as a conventional vacuum cleaner. The instrument collects the dust by circulating the air within a specially designed cyclone. The rotating current of air slows near the bottom of the swirling vortex, and suspended particles drop into a small bottle for later analysis.



COURTESY OF CS-3, INC.

CARBON MONOXIDE MEASURER uses an electrochemical cell as a gas sensor. The small electric current generated by the cell varies with the ambient level of carbon monoxide. By monitoring this current, an internal microcomputer can calculate the concentration of carbon monoxide and record its value at regular intervals.



BETH PHILLIPS



BETH PHILLIPS

PERSONAL SAMPLER records the particles and volatile organic compounds to which the wearer is exposed over the course of several days. Particles are trapped by forcing air through a filter with an electric pump, whereas volatile compounds are collected by letting air diffuse through a membrane onto charcoal disks.

lents, pesticides, solvents, deodorizers, cleansers, dry-cleaned clothes, dusty carpets, paint, particleboard, adhesives, and fumes from cooking and heating, to name a few.

Sadly, most people—including officials of the U.S. government—are rather complacent about such indoor pollutants. Yet if these same substances were found in outdoor air, the legal machinery of the Clean Air Act of 1990 would apply. If truckloads of dust with the same concentration of toxic chemicals as is found in most carpets were deposited outside, these locations would be considered hazardous-waste dumps. In view of the scientific results comparing indoor and outdoor exposure, it would seem that the time is now ripe for a major rethinking of the nation's environmental laws and priorities.

The initial version of the Clean Air Act, written in 1970, focused on outdoor pollution. Even in its 1990 revision,

the law has not changed much. It does not address the fact that Americans spend 95 percent of their time inside: despite all the evidence available today, the act still relies exclusively on measurements taken at outdoor monitoring stations. Many other U.S. laws pertaining to air pollution, hazardous waste, toxic substances and pesticides are similarly flawed, because they do not require accurate information on the levels of exposure people receive.

Although the absolute level of health risk posed by many toxic pollutants may be elusive, scientists can now accurately measure the exposure caused by different sources. Hence, to protect public health best, the broad suite of environmental laws should be reexamined and judged by how effectively they reduce people's total exposure rather than by how they reduce total emissions. That effort would surely be substantial, both to recast a large body of legisla-

tion and to monitor how well the laws work to reduce exposure. But the payoff would be a dramatic reduction in health costs as well as an improvement in the economy and effectiveness of environmental regulation.

Americans concerned about toxic substances do not have to wait for their government to make these far-reaching changes. Reducing exposure normally demands only modest alterations in one's daily routine. Yet people cannot take the simple steps required without adequate knowledge. So increased education is needed. Laws requiring more detailed labeling would also help: If a product contains a dangerous pollutant, should not the manufacturer be required at least to list the chemical by name on the package? Armed with a better understanding of the toxic substances found in common products and in other sources at home, people could then make their own informed choices. SA

The Authors

WAYNE R. OTT and JOHN W. ROBERTS have long studied environmental threats to health. Ott served for 30 years in the Environmental Protection Agency, managing research on air pollution, toxic substances and human exposure. He now does research in the departments of statistics and environmental engineering at Stanford University. Roberts helped to develop the surface samplers used by the EPA to measure pollutants in carpet dust. In 1982 he founded Engineering Plus, a small firm in Seattle specializing in assessing and controlling exposure to dangerous pollutants in the home. He works frequently with the master home environmentalist program in Seattle to help reduce the exposure of families to indoor pollutants.

Further Reading

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THE AMATEUR SCIENTIST

by Shawn Carlson

Bird-Watching by the Numbers

By a happy accident of geography, I live about as close to heaven as a bird-watcher can get. My area, near San Diego, Calif., is a natural way station for many North and South American varieties migrating along the Pacific coast, which accounts for the hundreds of exotic species that

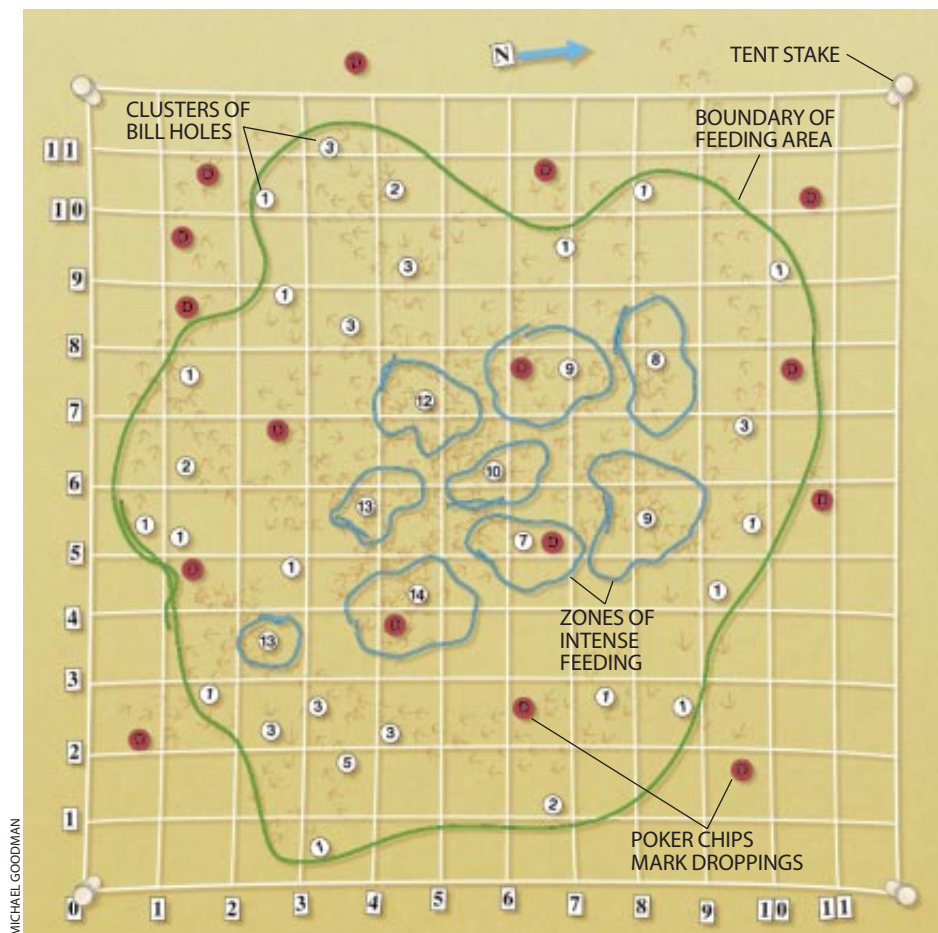
shorebirds. These three fascinating species have long been favorites of mine, and I have devoted many a delightful morning to uncovering the subtleties of their behavior. Sadly, some of my fellow bird-watchers roll their eyes in disbelief when they see me setting up my little laboratory on the beach. For example,

to discern complex relationships, a naturalist must carry out numerical measurements and chart the results. All professional scientists know this truth. Yet few amateur bird-watchers are aware that they could do even more to advance the scientific understanding of the natural world by quantifying their observations. So this month I offer a few ways to give bird-watching some quantitative teeth.

Although I developed these methods to examine California's shorebirds, the techniques are quite general and can help you to study the birds living in your neck of the woods. (In fact, similar methods could also serve in studying many other kinds of small creatures.) By comparing observations of many different species, interested amateurs might be able to separate behavioral patterns that sprang up recently from those that emerged early in the evolutionary history of birds, perhaps 100 or more million years ago [see "The Origin of Birds and Their Flight," by Kevin Padian and Luis M. Chiappe, page 38].

A good place to begin is by studying the traces birds leave on the ground. The best way to determine the relative location of such bird markings is to use a portable grid. Although a grid makes it fairly easy to draw a representation of the site on a sheet of graph paper, I suggest you use a camera instead. You can collect information most effectively if you spend your limited time in the field photographing interesting sites and then logging the observations in a notebook after the pictures have been developed.

To maintain accuracy, read the position of features on your pictures carefully using a ruler. Stay away from cameras that project an image of their own internal grid directly onto your photographs. That grid is always the same size on the film no matter how far away the subject, which makes it difficult to compare several pictures of the same



FEEDING SITE

for a flock of shorebirds can be charted using a fishing net as a grid.

seasonally pepper the landscape here. Indeed, the region harbors one of the most diverse ensembles of migrant birds to be found anywhere in the U.S.

Each year, I spy the first sparse flocks of whimbrels, marbled godwits and long-billed curlews, freshly arrived from their summer roosts in Canada, muscling turf away from San Diego's perennial

I'll often dash in and take over a spot where a flock has just been feeding so I can make measurements of their bill holes, footprints and droppings.

This kind of active scrutiny, aimed at quantifying the behavioral patterns of these animals, tends not to sit well in a community more used to observing birds passively through binoculars. But

site taken from different vantage points.

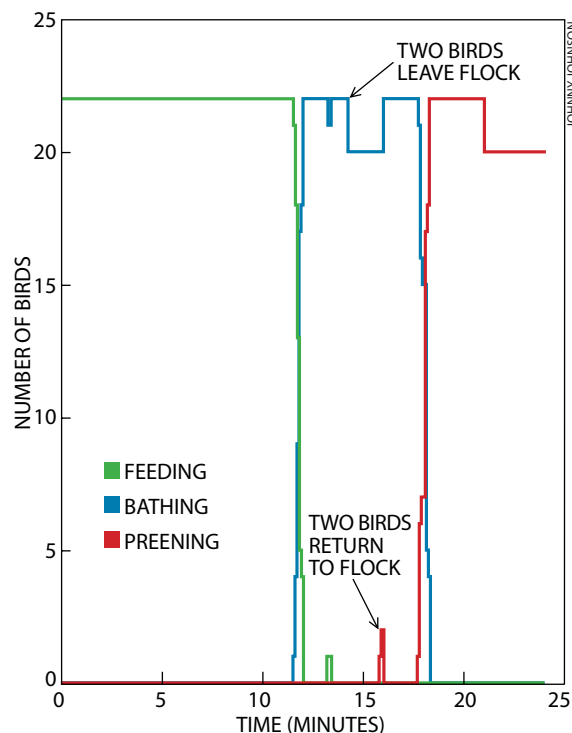
A nylon fishing net with a diamond-shaped mesh is ideal, because by tugging on it you can make the openings square. The size of your survey area will determine the optimum size of your mesh. If you are studying areas of a few square meters, a net with a five-centimeter mesh (about two inches) that is approximately three meters (about nine feet) on a side works well. Spray-paint the net a color that will stand out in your photographs. At your field site, secure one corner of the net using an old tent stake. Then use an L-bracket to guide the mesh into a square grid as you stake down the other three corners.

I do much of my research on the beach and have had a terrible time with joggers mindlessly running through my survey areas. They would often tramp directly on the site—even while I was standing there making measurements. I finally solved the problem by erecting a barrier around the perimeter with four vertical tent poles spanned by yellow-and-black “caution” tape.

To make grid coordinates obvious, obtain a set of numerals from your local hardware store—the kind used to indicate the addresses of houses. These tags will enable you to number the vertical and horizontal axes in a way that will show up in your pictures. The separation between the numerals will depend on the size of your site. Position them closer together (separated, say, by two or three mesh units) for a small site and farther apart (perhaps five or more mesh units) for a larger survey area. It never hurts to place an arrow and the letter N (also available from your local hardware store) in the frame to indicate magnetic north, so take along a compass.

Subtle features on the ground, like footprints or bill holes, are difficult to see in a photograph. Colored plastic poker chips provide a handy solution. For instance, suppose there are seven separate but tightly bunched bill holes in the sand. Mark that spot with a poker

chip clearly labeled with the numeral 7 drawn on an adhesive note with a broad-tipped black marker. A photograph of the site then documents the position of the chip on the grid and the number of feeding holes at that location, even though the holes themselves might not be visible. Indeed, you can easily re-



RAPID BEHAVIORAL SHIFTS,
*captured on videotape, show that whimbrels
in a flock tend to act in concert.*

cord different markings—bill holes, droppings, footprints—using a different color chip for each. Or you can dye some clothesline a bright color and use it to trace outlines around features of interest.

If a particular area needs a detailed explanation, a poker chip carrying a special mark (say, an asterisk) can refer to an entry in your field notebook. Be consistent with your use of colors for poker chips and clothesline. It doesn't matter what color scheme you adopt, but establish some convention and note it clearly in your notebook.

The illustration on the opposite page shows a feeding site for a group of 22 whimbrels. Diagrams such as this one allow amateur naturalists the opportunity to unravel fascinating details about these birds. For instance, my observations indicated that the number of droppings per unit area is much greater outside the feeding zone than inside it. This

arrangement suggests that whimbrels have evolved not to defecate where they eat—a strategy with obvious advantages. By knowing how many birds fed at this site and for how long, one can estimate the average number of droppings produced by any single bird feeding here per unit of time, which, though maybe not the most pleasant thing to think about, is a basic biological indicator of the health of the population.

The markings made at feeding sites such as this one are easily captured with a few photographs. But for recording the actions of animals as they happen, nothing beats a camcorder. You will want to have a protective carrying case, at least two extended battery packs and a tripod. Zoom capability, which lets you close in on your subject without actually moving toward it, is also helpful. But avoid the temptation to take only close-ups. Recording wide-angle views may allow you later to observe behavioral patterns of a group that you missed in the field.

Recently, after looking over some footage of a small flock of whimbrels feeding at the beach, I noticed that these birds showed a remarkably strong herd instinct. One bird started feeding, and in just 40 seconds the entire flock joined in. Several minutes later a different bird started bathing in the surf, and in less than a minute all the others had shifted from feeding to bathing. Then came group preening, then ear scratching, then head shaking. Over the course of an hour, the flock stepped en masse through six distinct activities.

Having the videotape made it child's play to see what was happening. The speed at which the group shifted between behaviors [see graph at left] was striking. Why have these birds evolved to act in this way? No one knows, but perhaps with a coordinated study, dedicated amateur bird-watchers can help solve the riddle.

For more information about this or other amateur science projects, join the discussion on the Society for Amateur Scientists's World Wide Web site: link to www.thesphere.com/SAS/ and click on "Forum." You can also write the society at 4735 Clairemont Square, Suite 179, San Diego, CA 92117, call (619) 239-8807 or leave a message at (800) 873-8767.

Tight Tins for Round Sardines

The party game “sardines” involves packing as many people as possible into a closet. Mathematicians, too, like to play sardines, but both people and fish are awkward shapes, so they prefer circles. What, they ask, is the smallest size of square crate into which you can pack 49 milk bottles? Or equivalently, given a unit square, what is the diameter of the largest circle, 49 copies of which can be packed inside the square without overlapping?

To see that these questions are equivalent, note that solving one problem automatically solves the other, after a simple rescaling. Provided, of course, that one doesn’t put milk bottles in upside down or on their sides.

Nearly all the information we have about such questions dates from 1960 or later. The reason is that “combinatorial geometry,” as this area is known, is surprisingly subtle. For example, surely it is obvious that the smallest square crate into which you can pack 49 milk bottles of unit diameter has a side of seven units: just arrange the bottles in a

square array. Obvious, but false. In 1997 Kari J. Nurmela and Patric R. J. Östergård of the University of Technology in Helsinki found a way to pack 49 circles inside a slightly smaller square.

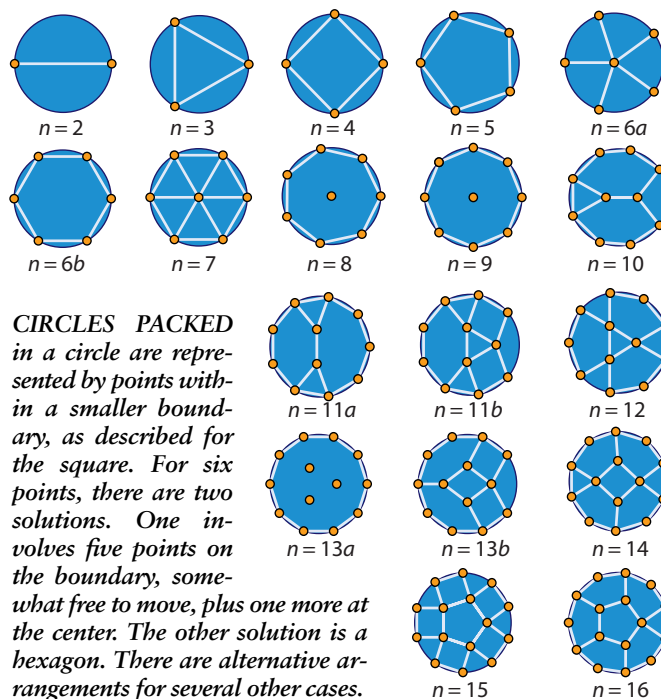
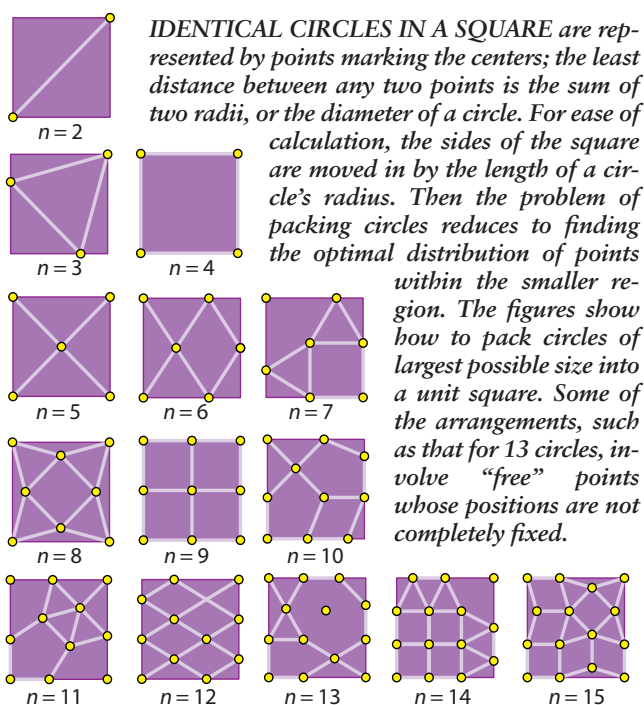
German mathematician Gerhard Wengerodt had already shown that the obvious square packing is optimal for 1, 4, 9, 16, 25 and 36 circles but not for 64, 81 or any larger square number.

The square packing ceases to be optimal for some sufficiently large number of circles. In the infinite plane the densest packing is not the square lattice but the hexagonal one—like the arrangement of balls at the start of a game of pool. A square boundary prevents a perfect hexagonal lattice from forming, which is why small numbers of circles yield square arrangements. When the number gets big enough, however, the effect of the boundary becomes so small that solutions close to a hexagonal lattice can pack in more circles than the square one.

I recently received a doctoral thesis examined at the University of Utrecht in December 1997, *Packing and Cover-*

ing with Circles, by Hans Melissen. It is by far the best and most complete survey of such questions that I know. The problem of packing equal circles inside a square, while maximizing their size, seems first to have been discussed in print in 1960. At that time, Leo Moser conjectured a solution for eight circles. It was verified soon afterward and led to a series of publications on the same question with different numbers of circles. In 1965 Jonathan Schaefer, then at the University of Alberta, one of the mathematicians who proved Moser’s conjecture, published solutions for up to nine circles. He remarked that optimal packings for up to five circles are easy and attributed the solution for six circles to Ronald Graham, now at Lucent Technologies’s Bell Laboratories.

Mathematicians usually reformulate the problem so that the circles themselves disappear from consideration. If two equal circles touch, then their centers are separated by a distance equal to their common diameter. And if a circle touches a straight boundary, its center lies on a line that is parallel to the boundary but separated from it by a distance equal to the radius. If we represent the circles by their centers, the



problem can be rephrased as: "Place 49 points (centers) in a given square in such a way as to maximize the minimum separation between any two of them." The circles' diameter is then the smallest separation between any two points. But the square is not the original; it is a smaller one, with sides that have been moved inward by an amount equal to the radius.

The advantage of the "point" formulation is its conceptual simplicity. The optimal arrangements for up to 15 circles are summarized in the left illustration on the opposite page. A trickier variant concerns packing circles (or equivalently, points) inside a circle. The earliest known publication on this question is the 1963 Ph.D. thesis of Boele L.J. Braaksma of the University of Groningen in the Netherlands, on a technical question in analysis. In among the technicalities, he conjectures an optimal arrangement for eight points; he later found a proof, which he never published. The solutions are now known for 11 and fewer points. Optimal arrangements for between 12 and 20 points have been posited, but proofs are lacking.

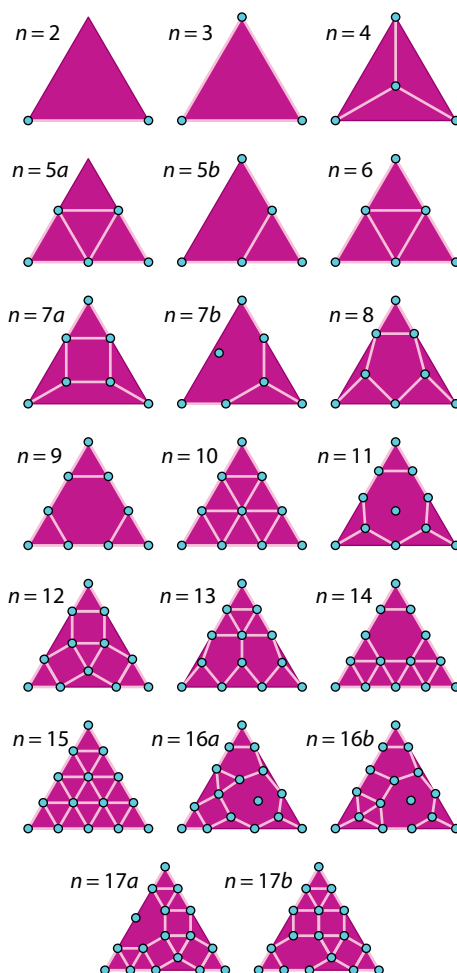
The proof for 11 points was first provided by Melissen. He begins by partitioning the circle into a system of curiously shaped regions and estimates distances to show that some of these regions contain at most one of the points that are to be distributed inside the circle. In this way, the investigator gradually gains "control" over the disposition of the points—establishing in this case that eight of the points must lie on the boundary of the circle. The method is delicate and relies on an intelligent choice of the partition. It is, however, general enough that some version of it can be used on many such problems, often with the aid of computer calculations.

Packings inside an equilateral triangle are especially interesting, because this boundary relates rather neatly to the hexagonal lattice, as any pool player knows. The wooden or plastic frame used to set up the balls is an equilateral triangle, and the balls inside it pack together as part of a hexagonal lattice. In fact, such packings were first studied only when the number of circles was a triangular number, of the form $1 + 2 + 3 + \dots + n$. Such numbers of circles—1, 3, 6, 10, 15 and so on—can be distributed in part of a perfect lattice packing.

The hexagonal lattice is known to be the optimal arrangement over the whole plane, a fact widely assumed but first proved by Axel Thue in 1892. It is therefore highly plausible that the optimal packing of a triangular number of points inside an equilateral triangle is the obvious pool-ball arrangement. This is in fact true, but a proof is quite tricky: Melissen gives a particularly neat one. He also finds (and proves) optimal arrangements for 12 and fewer points, together with conjectures for 16, 17, 18, 19 and 20 points.

The packing question can even be posed on curved surfaces. In 1930 the Dutch botanist Pieter M. L. Tammes asked for optimal packings of circles on the surface of a sphere [see "The Kissing Number," *Mathematical Recreations*; *SCIENTIFIC AMERICAN*, February 1992]. Melissen considers a variant of the Tammes problem, using not a sphere but a hemisphere. He proves the results for six and fewer points but only conjectures them for seven to 15 points. (For those feeling really ambitious, what about packing spheres in three-dimensional regions?)

In 1985 Alexander A. Berezin of McMaster University in Ontario published a short note in *Nature* about minimum-energy configurations of electrically charged particles inside a

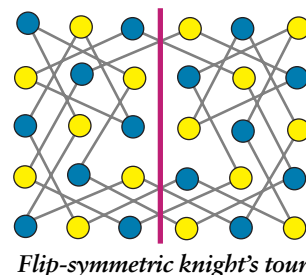


TRIANGULAR BOUNDARY
favors hexagonal patterns of points.

FEEDBACK

I make no apology for returning to the subject of knight's tours (April 1997 and Feedback for September 1997). Richard Ulmer of Denver has sent me a highly informative letter on the topic, about which he is writing a thesis. He noted that my 6×6 tour is one of the 10 tours (out of 9,862 in total) to possess 90-degree rotational symmetry. I had remarked that the smallest value of n for which there is a tour on the $3 \times n$ board is 10. He calculates that there are exactly 16 tours on this board, 176 on the 3×11 board, 1,536 on the 3×12 , and so on up to a staggering 107,141,489,725,900,544 distinct tours on the 3×42 board. There are eight solutions on the 5×6 board, 44,202 on the 5×8 , and 13,311,268 on the 5×10 .

Ulmer also notes that no knight's tour can have diagonal flip symmetry. On a rectangle whose two sides are even numbers, no tour is symmetric about a major axis. When the vertical side is odd, a tour with horizontal flip symmetry is still impossible. Flip-symmetric knight's tours do exist on some boards (right). Specifically, they can occur when one side is odd and the other is twice an odd number. Ulmer's current conjecture is that—perhaps with a few small exceptions—flip-symmetric tours exist on all such boards.

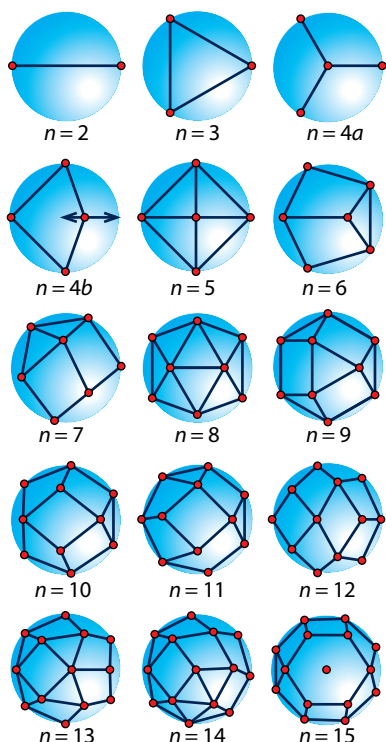


JENNIFER C. CHRISTIANSEN

disk. This problem has the mathematical flavor of circle packing, because the particles repel one another. What really counts, however, is not separation as such but energetic balance—the system minimizes its total energy. At any rate, the prevailing intuition was that the charges should push one another to the edge of the disk. But Berezin's numerical calculations showed that for between 12 and 400 electrostatic charges, the distribution with one at the center and the rest at the boundary has lower energy than that with all at the boundary.

The discrepancy between physical intuition and Berezin's computations was eventually resolved in favor of physics. The real physical universe does not include infinitely thin disks. In reality the central point tends to migrate a tiny distance away from the true center of the disk and is then pushed to the boundary.

The problem still has much interest, however; for example, Melissen gives the first rigorous proof that Berezin's numerical results are correct. So technical difficulties notwithstanding, much progress is now being made on these elegant, baffling questions. And I look forward to hearing of more. SA



HEMISPHERE forces a different set of patterns than a flat circle because of the curvature of the surface.

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REVIEWS AND COMMENTARIES

TILL A LAST WIND'S BREATH

Review by Marguerite Holloway

Rachel Carson: Witness for Nature

BY LINDA LEAR

Henry Holt and Company, New York, 1997 (\$35)

She is standing in profile, head tilted upward, unsmiling, concentrating; she seems immensely still. This black-and-white portrait (*below*), the cover illustration for Linda Lear's biography of Rachel Carson, feels like a gray day at the seashore. The grainy, calm image immediately establishes what Lear makes clear in her exhaustively researched, voluminous book: the famous conservationist, scientist, author of *Silent Spring* and three lyrical books about

the oceans, was solitary, serious and close to a force of nature herself.

In *Rachel Carson: Witness for Nature*, Lear explores the roots of Carson's powerful, visceral connection to the natural world, to writing and to science. And by placing Carson's influences, complexities and accomplishments in their historical context, Lear—a professor of environmental history at George Washington University, who is also affiliated with the Smithsonian Institution—de-

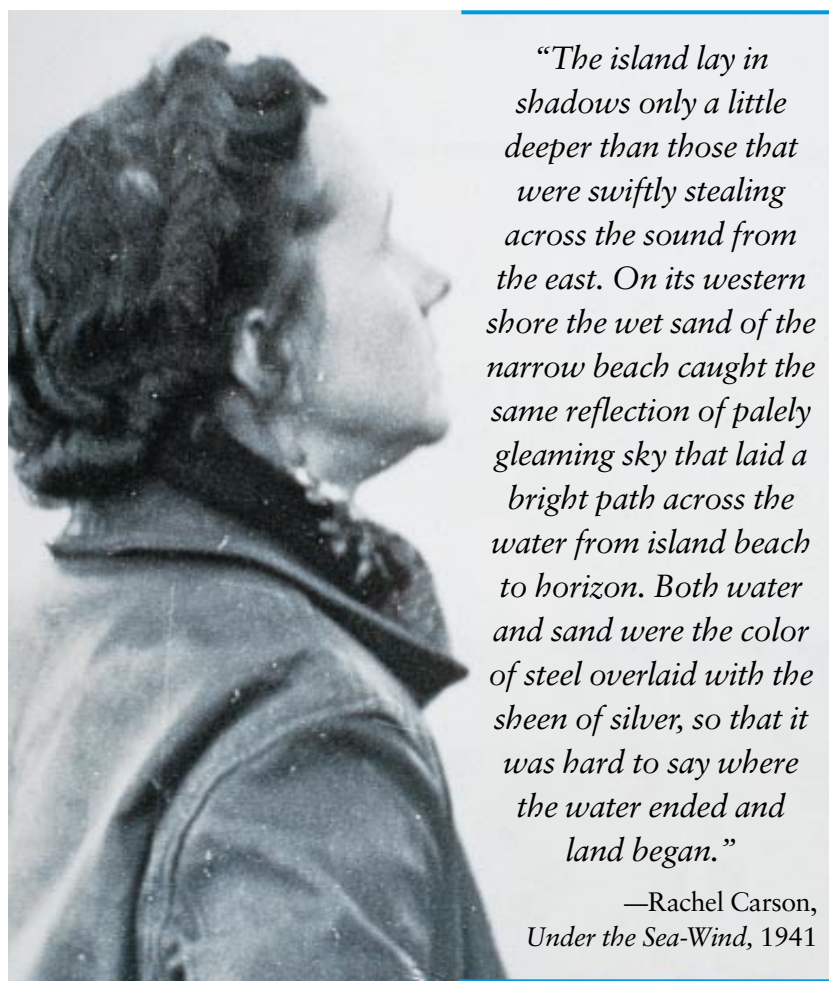
scribes the profound effect that this writer and thinker had on American society.

The book begins and ends with Carson dying of cancer, shortly after *Silent Spring*—which was published in 1962—began to galvanize the country to ban the use of the pesticide DDT. This circularity imparts a sense of fatalism to the biography as well as to Carson's life. Deep respect for and love of nature inevitably drove Carson to what was an entirely unlikely role for an intensely private, socially awkward person: that of advocate and catalyst.

Carson was born in 1907 to a somewhat troubled family. Her father was generally absent, and her two siblings were older and often without moorings—something that later became a burden to Carson. She spent most of her childhood with her mother, Maria, reading aloud, studying and exploring the Pennsylvania countryside. Maria's respect for nature was such that she would have her children return to the forest the items they had collected on their walks. "This kind of care for the natural world had a spiritual dimension that at least her youngest daughter embraced and would practice all her life," Lear writes.

Indeed, whatever Carson wrote about the environment was infused with spirituality, as is evident in this passage from a draft of her 1955 book, *The Edge of the Sea*: "There is symbolic as well as actual beauty in the migration of the birds; in the ebb and flow of the tides, responding to sun and moon as they have done for untold millions of years; in the repose of the folded bud in winter, ready within its sheath for the spring. There is something infinitely healing in these repeated refrains of nature, the assurance that after night, dawn comes, and spring after the winter."

From the outset, Carson was as drawn to reading and writing as she was to nature. At the age of 11 she published her first short story, and when she entered the Pennsylvania College for Women, she expected to pursue her literary interests. But there she became enamored of biology, because, as Lear describes, it "revealed yet another way for Rachel to love nature." She went on to graduate work at Johns Hopkins University,



"The island lay in shadows only a little deeper than those that were swiftly stealing across the sound from the east. On its western shore the wet sand of the narrow beach caught the same reflection of palely gleaming sky that laid a bright path across the water from island beach to horizon. Both water and sand were the color of steel overlaid with the sheen of silver, so that it was hard to say where the water ended and land began."

—Rachel Carson,
Under the Sea-Wind, 1941

SHIRLEY A. BRIGGS

Star Wars: The Magic of Myth

Exhibition at the Smithsonian Institution, National Air and Space Museum, Washington, D.C.

Companion volume by Mary Henderson, Bantam Books, 1997 (\$24.95)

A long time ago in a galaxy far, far away...." The fairy-tale opening of George Lucas's 1977 movie *Star Wars* set the stage for a blockbuster trilogy that has become the stuff of cinematic legend. And through October 1998 the eclectic enchantment of *Star Wars* is re-created at the National Air and Space Museum in Washington, D.C. In *Star Wars: The Magic of Myth*, the museum plays host to a cosmic menagerie of Jawas, Tusken raiders and Imperial storm troopers, not to mention the ludicrous droids R2-D2 and C-3PO. The exhibit and the companion volume by its curator offer insightful commentary on the luxuriant symbolism of Lucas's "alternative universe."

The costumes and production models on display illustrate Lucas's cleverness in creating not just a futuristic world of gleaming metal and over-friendly machines but one that is also ancient and battered, filled with characters drawn more from the imagery of medieval romance than from science fiction. The strategy works. We recognize the wizened guards and the virginal princesses from stories we have heard. Leather bindings, wooden accoutrements and frayed sackcloth are more prominent than Lycra and precision robotics, and Lucas ensured that the spaceships in his tale were well rubbed with dirt before he let the cameras roll. Only Princess Leia remained unsullied.

In the forms of the strange creatures that lurk behind every pillar, too, Lucas borrowed shapes and textures familiar from a trip to the zoo. Greedo's face is a cross between that of a tarsier and a hatchet fish; Chewbacca is a friendly orangutan. And surely Jabba the Hutt's amphibian squint and bulging belly are made all the more abhorrent by his taste for live

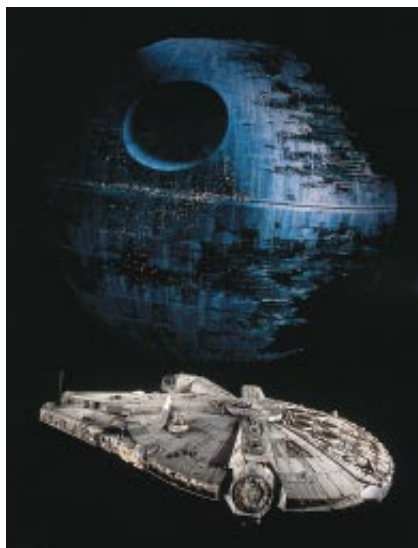
toads. Naturalistic touches such as these remind us that what we are seeing is really not so implausible.

Mythological interpretations of the elements in the hero's journey of Luke Skywalker are outlined at appropriate points in the exhibit and explored at greater length in the book.

This decoding of the story, expanded (with due credit) from the late Joseph Campbell's *The Power of Myth*, shows that the fairy-tale quality of the saga is far from coincidental. Indeed, Lucas, in a taped interview that visitors can watch, explains how he spent two years studying mythology when he was writing the *Star Wars* scripts. No wonder we feel the hand of fate at work when a plea for help serves as Luke's call to adventure. It was ever thus with damsels in distress, as Perseus learned with Andromeda. And it should be no surprise when a fatherly magician gives Lucas's hero an Excalibur-esque light saber.

High technology, of course, appears in the *Star Wars* movies in the horrific, labyrinthine Death Star, a space battle station capable of exploding entire planets. In the exhibit, a few malevolent minions serve as tokens of the dehumanizing dark empire and the

wheeling prince of evil incarnate, Darth Vader, whom Luke battles as a rebel fighter pilot. The fascist symbolism in the empire's force is blatant, as is the significance of our gunslinging rescuers' leather holsters. The mystical, invisible Force is not on display, but its message is nonetheless clear: we want technology on our human terms, not its own impersonal ones. Whatever is lacking in subtlety in Lucas's cinematic creations is more than compensated for by their exuberant inventiveness. Nostalgia is worth a visit. —Tim Beardsley



ARCHENEMIES,
the Death Star (top) and
the Millennium Falcon

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spending some summers at the Marine Biological Laboratory in Woods Hole, Mass., studying marine life.

In the mid-1930s Carson joined the Fish and Wildlife Service, where she became an editor and writer. In this position, Carson began to realize her mission. She wrote pamphlets, articles, speeches and books about nature, conservation and, particularly, the oceans—bridging the gap between the worlds of literature and of science. Lear explains that Carson never saw the sea until she was in college, but when she did, she began to see that the story she wanted to use her

life to tell was the story of the oceans.

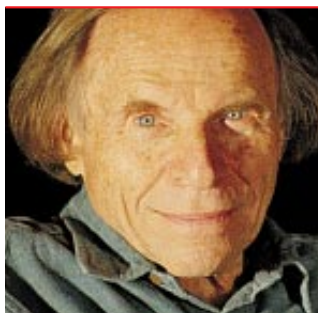
Her three poetic books did just that. *Under the Sea-Wind* (1941), *The Sea Around Us* (1951) and *The Edge of the Sea* transformed many Americans' relationship to nature. At one point in 1952, her first two books were both on the *New York Times* best-seller list.

Lear chronicles what seems to be every detail of Carson's life, friendships and work. Although this is a monumental accomplishment—a quick glance at the sources, bibliography and 94 pages of notes conveys just how monumental—the information weighs heavy at

times. Carson's concerns about finances, for instance, provide an important insight into her character. Yet Lear's inclusion of so many financial transactions is dulling, as is the record of what seems like every exchange with Carson's editors and publishers.

Lear's writing does not have the poetic grace of her subject's works, but it does have everything else Carson strove for: exactitude, thoroughness and context.

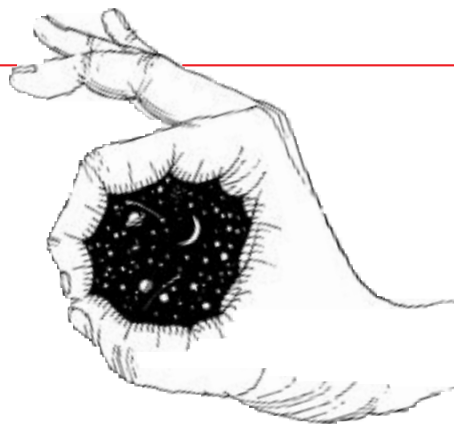
MARGUERITE HOLLOWAY is a contributing editor for SCIENTIFIC AMERICAN.



WONDERS

by Philip Morrison

The Star Mapper



DUSAN PETRIC

Our galactic star precinct has just been well mapped for the first time, ready for a century of searching stars for the promise of life. A terabit of data from a European Space Agency satellite called Hipparcos underlies a magnificent list of over 100,000 star distances of unprecedented accuracy out to nearly 500 light-years. You can buy this 1997 gazetteer in 16 printed volumes—unless it's sold out. Digitally secure people can have it all compactly via CD-ROM.

Here we offer an account of the remarkable life and work of this robot surveyor out in clear space. We are talking angles, angles that subdivide the sky. Dividing any circle into equal segments of arc is a well-posed task: the length is not important, for there are no ends. You need agree only on the subdivision. The choice long ago in Babylon was 360 degrees, appealing when arithmetic was a skilled craft and maybe clinched by the hint of days in a year. One degree of arc was and is parted into 60 small arc minutes, and one minute of arc is divided further into 60 exquisitely small arc seconds. Mountaintop observatories at their best see stars as half-second disks of twinkling light. Hipparcos offers a median error of a thousandth of an arc second, possible because it is outside of all the restlessly varying air. With that acuity, you could make out a poliovirus particle across the room.

The first precision sky surveying was done about 1840, before photography, by astronomer Frederick Bessel, along with a master of instrumentation, Joseph Fraunhofer. Between the two of them they built an original instrument based on a telescope eight feet long, with a six-inch split lens. The stars showed up in its eyepiece as doubled spots. Micrometer screws allowed the patient observer to shift the lens halves until the two image spots coincided. By moving

a star image until it coincided with another reference star, any image shift could be measured. By viewing the same nearby star after half a year's wait, Bessel could measure the star's apparent shift caused by his own movement, along with Earth, across the known diameter of our planet's annual orbit.

An analogy is familiar. While you watch from a moving car, the roadside trees shift in direction rapidly, whereas a tree far across a wide field hardly shifts at all. The car would form the base of a triangle by its known motion, and out in the field the tree would lie at the apex. The stars behave the same way, but their shift in direction is amazingly small. The altitude of Bessel's extreme triangle to the star 61 Cygni was about 300,000 times as long as its base! The center of the reddish splotch of the star shifted only a few thousandths of

*We are talking angles,
angles that subdivide the sky.*

an inch during one round-trip on Spacecraft Earth. The triangle's apex was 10 light-years away, the first firm milestone among the stars.

This elegant, patient art, called astrometry, remains vigorous. With the right telescopes, its adepts have laid out hundreds of measured triangles to close stars, building the platform for the rickety, many-runged ladder of big cosmic distances. All other longer cosmic distances depend on ingenious but risky assumptions, supplying estimates calibrated by a chain of links to those few but reliable if very pointy triangles.

The European Space Agency moved astrometry out into the cosmos on Hipparcos, built to divide the circle into a billion steps of tiny arcs, about one milli-arc second each. Star images were seen at the modest resolution of its 11-inch

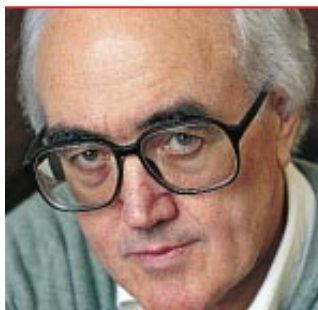
telescope, but the images were steady. It scanned the entire limpid sky, lived in microgravity too small to distort parts as the probe turned, and kept tight temperature control over the graphite-fiber telescope mounting. This astrometric station was scrupulously monitored and superbly stable.

Hipparcos was given a wonderful legacy, its *Input Catalogue*, endowing it with the then best of ground astrometric data. From launch late in 1989 to mid-1993, the satellite watched the sky. The first processed results began to appear in the spring of 1997, for each star sighting took meaning only after elaborate comparisons with many others.

Four distinct teams—hundreds of astronomers, engineers and data mavens—worked long at the task. They had been confronted by a sudden, daunting failure on launch; the rocket did not put Hipparcos into the planned geostationary orbit. As Earth then turned beneath Hipparcos, no single ground station could collect the day's stream of data beaming downward by radio. Quickly, however, not one but three ground stations were set up around the world. In the end two thirds of all expected data came in, a triumph of masterful salvage in space.

How does it work? The satellite scanned the sky as it orbited, spinning on its viewing axis. Its long, elliptical Earth orbits took 10 hours, sampling stars in a belt about a degree wide in the sky. Meanwhile the auxiliary star-mapping detectors picked up catalogued guide stars to find approximately where the axis pointed and thus to identify which stars were being seen. Every star signal that entered the optics crossed a couple of thousand slits in the main electronic sensors as the probe spun, the light registering as voltage pulses. Indi-

Continued on page 102



CONNECTIONS

by James Burke

Local Color

*Sexual peccadilloes were
a habit Prosper failed to break.*

We've been doing some home decorating recently, and I was rejecting a fairly bilious shade of avocado when I suddenly remembered the French Empress Eugénie, who went to the Paris Opera one night in 1863 and blew everyone away by wearing a green silk dress.

Not just any old green, though. This was aldehyde green. The latest high-tech product to come out of that well-known chemical treasure trove, of which I have spoken many times, coal tar. And the reason Eugénie's dress was such a sensation was that the green didn't look blue under gaslight. Earlier that year a German chemist called Lucius had discov-

ered the color. Apart from astonishing operagoers, the new dye also contributed to the success of his company (which later changed its name to Hoechst).

Now, I don't know which opera Eugénie heard that night. Pity she never heard *Carmen*, which would not be performed until 1875, after she had already gone into exile. That opera's story line had been provided by Eugénie's mother, Countess of Montijo, in Spain. Back in 1830 she had told the story to Prosper Mérimée when that writer had turned up at the Montijo family home and charmed everybody, including the five-year-old Eugénia, as she was then called. Mérimée went on to use *Carmen* for the

novel on which Bizet would later base his opera.

Mérimée remained in close touch with Eugénia. This may be why, years later when she met and married the Emperor Napoleon III, she mentioned her best pal Prosper, who was promptly given the title of senator and oodles of boodle to support him while he wrote plays and novels. Just as well the Emperor didn't know Prosper had been having an affair (one of many) with his uncle's mistress. Sexual peccadilloes were a habit Prosper failed to break for most of his life, starting with a scandal while he was still at school.

Continued on page 102

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and the Natural Sciences**

Wonders, continued from page 100

vidual stars generated long strings of pulses over time—some 2,000 stars during each 10-hour orbit. After years of gathering multiple signals, Hipparcos began to pull out the positional information entangled in this huge database. Because of the precision with which the relative positions of the stars were timed, Hipparcos was able to record thousands of tiny parallax-induced shifts for individual stars at different points in Earth's orbit as the satellite rounded the planet again and again.

The *Input Catalogue* began the whole process; each program star was revisited about 100 times, far overdetermining the numbers needed to locate a star. That prodigious session of years of heavy computation was planned and executed by two firmly independent expert teams. Their iterations led to consistent positions for each of the 100,000 stars, with errors noted. Named for the star cataloguer and savant of ancient Rhodes (cited as a major source by old Ptolemy himself centuries later), Hipparcos has mapped our local star neighborhood anew. In one decade it has advanced all ground-based astrometry by 100-fold in coverage, making fivefold or 10-fold gains in precision as well. It confirms most well-regarded astrometric distances to a few percent.

Has our locality been mapped for the last time? Hardly. The Cepheid class of very bright variable stars is marked by peculiarly regular light curves: the faster the pulsed cycle, the brighter the star. Thus recognizable from far away by their timed pulses, Cepheids are major sources for the Hubble distance scale. Hipparcos distances move out by about 20 percent the few nearby Cepheids whose distances were calibrated earlier. That implies a slower expansion, hence an older cosmos, comfortably reducing the conflict between redshift age and luminosity age for external galaxies.

A masterstroke of recalibration? Maybe. There is a long, uncertain chain of theory between the distance to a Cepheid and the age of a remote cluster. Nor do all the rich Hipparcos results yet concur. We cannot assume that good calibration is all we need. But one day sufficient benchmarks in many wavebands will indeed pin down the grand cosmic map to microarc seconds, a solid foundation. Patience.

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Connections, continued from page 101

Where one of his best friends was a far less interesting type named Adrian de Jussieu. The last in a long line of botanists, he took over from his old man when the latter retired from the Jardin des Plantes. Followed in the footsteps, really, and not much else. But Adrian's daughter married a guy who really did make a mark. Name of Armand Fizeau, who in 1849 worked out the speed of light with a crafty gizmo consisting of a 720-tooth cogwheel, spinning very fast. He shone a light beam at the cogs and a mirror, several kilometers away behind the cogwheel, which reflected the light when there wasn't a cog in the way. By relating the speed of the wheel to the point at which the cogs eclipsed the light, Fizeau was able to say that light moved at 315,000 kilometers per second. Pretty close to what we now know to be 299,792.458.

His close collaborator in all this was, like Fizeau, an ex-medical student who couldn't stand the sight of blood: Léon Foucault. In 1845 both of them took the first clear daguerreotypes of the sun's surface. It was while working out a mechanism for keeping the camera pointed at the sun (and later at stars) for long exposure times that Foucault invented his great pendulum. That same year he had met a diffident young Briton, William Thomson, while studying at Henri Regnault's lab in Paris. Thomson, later Lord Kelvin of absolute zero fame (in one sense), went on to similarly great things. Least of which was developing a theory to explain the way certain crystals responded to changes in temperature by becoming magnetic. He showed that there was a relation between temperature and the permanent polarity of these crystals.

Back in 1824 this phenomenon had been named "pyroelectricity" by Sir David Brewster. This hardy Scot had failed to be a tutor, editor, preacher and love-poet, so he settled for science, focusing on polarization of various kinds and

inventing the kaleidoscope. The instrument was primarily for designing patterns in carpets, wallpapers and fabrics. Well, why not? Eventually, through what reference books describe as being "zealous in advancing long-neglected areas of science" (he sounds like a modern doctoral candidate!), Brewster proceeded by leaps and bounds toward attaining important medals and the principalship of Edinburgh University.

Brewster married Juliet, youngest daughter of James MacPherson, the man who changed the path of cultural history when, after touring the Scottish Highlands, he pretended to have discovered a great third-century Gaelic epic poem written by a Celt named Ossian. This apparently archetypal bit of ancient European self-expression hit the philosophical world (and in particular the German one) like an earthquake. With its portrayal of an earlier, simpler existence, the epic almost single-handedly triggered the Romantic movement. Its portrayal of an ancient warrior society of superbeings would one day give the Nazis a few ideas. Even Thomas Jefferson thought Ossian must have been "The greatest poet that ever existed!" Not bad press for what was, within decades, discovered to be a fake. Three years after the poem was published, in 1763, and MacPherson had become a literary lion in London society, he got the job of secretary to the governor of Florida—thanks to the good offices of the Earl of Bute—and left for America.

Bute himself is remembered as a thoroughly unpleasant politico who was prime minister for a year. And is forgotten for his pivotal influence in getting the Prince of Wales to set up what was to become one of the greatest Botanic Gardens in the world at Kew, outside London. Bute had been a keen gardener for years, and in 1757 he persuaded Princess Augusta to appoint Sir William Chambers as architect to the gardens.

Four years later Chambers built the amazing Kew pagoda, 163 feet of the most detailed example of chinoiserie in Europe—quite something if you like that kind of stuff. Conforming to the overblown style of the times, he also



DUSAN PETRIC

added a mosque, an "Alhambra," various classical temples and an imitation Gothic cathedral. This made Chambers the master of the garden temple genre and a shoo-in for the commission to build Somerset House, a gloomy, grandiose heap that is today the home of the British Internal Revenue. Serves it right.

Chambers shared the commission with Robert Adam, one of the most influential stylists in architectural history. It was he who, when he returned from a Grand Tour of Europe discovering the beauties of Roman and Greek ruins, turned the facade into an art form. Adam set about

persuading the English aristocracy that their moldering piles would look so much better with Doric front doors and colonnaded wings. When he'd finished, anybody who was anybody lived in something that looked like a bank.

Adam's runaway success meant he had many imitators. One of whom, George Dance, "Adamized" a minor stately home called Camden Place, in the Kentish village of Chislehurst. At one point, late in the 19th century, it was rented by its minor aristocrat owner to an exiled empress who wore green silk dresses.

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WORKING KNOWLEDGE

HYDRAULIC BRAKES

by Stanley L. Stokes
Society of Automotive Engineers

Hydraulic brakes play a critical role in the safe operation of any passenger vehicle. Until the 1930s, most brake systems relied solely on mechanical force from the driver's foot applied to the brake pedal. Rods or cables directed this force to press brake shoes against a drum, which slowed the wheels. Hydraulic braking systems, in contrast, employ fluid under pressure to apply greater and more uniform braking forces. Pushing the brake pedal activates pistons contained in a master cylinder that transforms the applied force on the pedal into pressure throughout the hydraulic system, causing pistons in the wheel cylinders to activate either drum or disc brakes. Because the area of the hydraulic cylinders in the wheel is larger than

the area of the master cylinder, the applied force is amplified.

In the 1950s the advent of power brakes, which augment hydraulic pressure still further, also reduced the effort required by drivers. For added safety, modern brakes divide the hydraulic system to prevent a complete loss of braking from failure of one of the two subsystems. Fluid moves to the brakes when two pistons in the master cylinder are activated. Each piston serves just one set of wheels. In the newest designs, each subsystem routes fluid to diagonally opposite wheels rather than just the front or back wheels. This approach ensures more equal braking in the case of failure in one subsystem—providing a measure of redundancy for the car's most important safety mechanism.

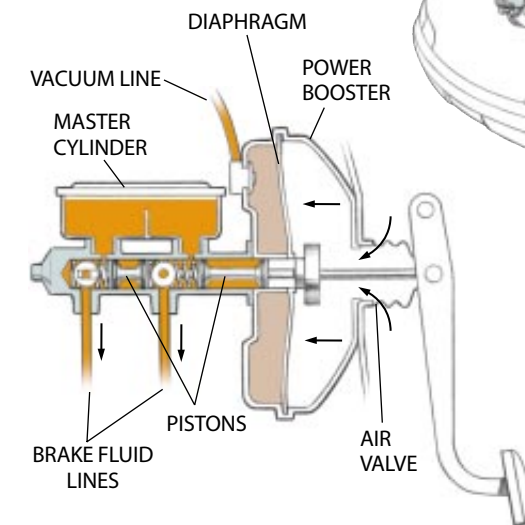
GEORGE HETSECK

DEPRESSING BRAKE PEDAL

triggers a chain of events in which a master cylinder converts force on the pedal to pressure that activates disc or drum brakes.

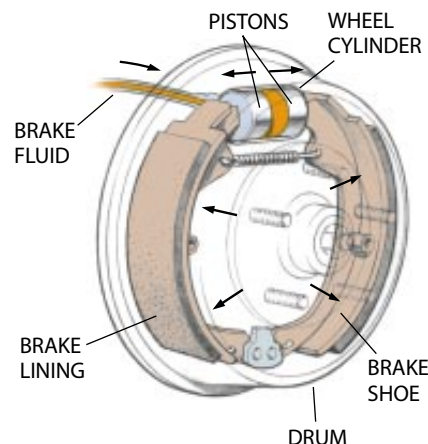
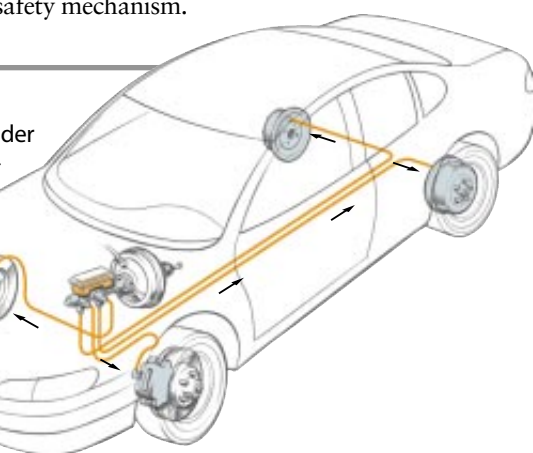
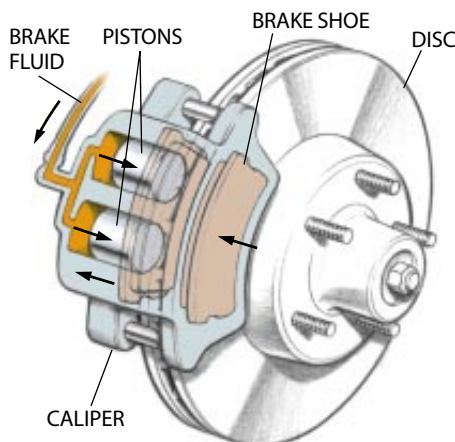
POWER BRAKE

involves a master cylinder and power booster connected as a single unit. When the brake pedal is not engaged, a vacuum surrounds the large diaphragm. Depressing the pedal opens a valve that allows air to enter on one side of the diaphragm, restoring atmospheric pressure. The pressure difference between the two sides then forces the diaphragm inward, actuating pistons in the master cylinder. This action boosts power to the hydraulic system. Brake fluid displaced by this movement triggers pistons in cylinders at each wheel; the pistons then activate drum or disc brakes.



DISC BRAKE

typically fits on the front wheel, where the dissipation of heat from the friction of stopping is most needed. The pistons in the brake caliper force the linings on the surface of the brake shoes to clamp against both sides of a metal disc (or rotor). Friction slows the spin of the rotor—and the wheel to which it is attached. Some newer cars have disc brakes on all four wheels.



DRUM BRAKE,

usually placed on a rear wheel, consists of a wheel cylinder between the movable ends of two brake shoes. The cylinder's two pistons force the shoes outward toward the drum when the pedal is applied. The linings on the brake shoes push against the inner surface of the drum. The resulting friction stops the wheel from turning.